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What scientific information on the seismic risk to non-structural elements do people need to know? Part 1: Compiling an inventory on damage to non-structural elements

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Abstract

Understanding seismic damages to non-structural elements and their effects on functionality of facilities are important in developing general recommendations for earthquake risk management. This paper presents a review of non-structural damage caused by recent earthquakes in Mt. Etna in Italy, Lisbon and Azores islands in Portugal and southern Lowland in Iceland. The study was performed as a part of the KnowRISK EU project. The objective of this review is to identify the most commonly damaged non-structural elements in these different areas. This is a basic requirement for preparing prevention strategies communication campaigns that are tailored to the local needs. This study shows that the most commonly damaged elements are partition walls, ceiling systems, non-structural vaults, chimneys, building contents and storage racks. Analyses proved that substantive efforts are needed worldwide to improve techniques for reducing damage to non-structural elements. The observations on frequency, severity, and consequences of damage of different non-structural elements are important for (i) making mitigation plans and priorities (ii) designing mitigation measures, and (iii) communicating the mitigation measures to different stakeholders. These activities aim to raise stakeholders' awareness of potential risk and viable mitigation measures.

Keywords: non-structural elements; most frequent damage; Mt Etna; 1969 and 1998 earthquakes Portugal; 2000 earthquake Iceland.

1. Introduction

Recent earthquakes in countries with codified seismic design provisions have shown that losses from damage to non-structural elements (NSE) have often exceeded those from structural damage (Filiatrault and Sullivan, 2014). Non-structural damage (NSD) can lead to injuries and possible fatalities, economic loss associated with the disruption of business and livelihoods, as well as those associated with repair/restoration operations. NSD, therefore, reduces societal resilience to earthquakes, and resilient societies need to mitigate them. Understanding the nature and extent of damage to NSE and their consequences are essential for any meaningful disaster risk management effort.

This work is based on extensive reviews of NSD caused by recent earthquakes in three pilot areas studied inthe KnowRISK project (https://knowriskproject.com/). These study areas are Mt. Etna volcanic region in Italy, Lisbon and Azores Islands in Portugal and the southern lowland in Iceland. Quantitative data on NSD damage is usually scarce, as post-earthquake reconnaissance surveys (or studies) have so far focused more on structural safety issues such as building usability. A systematic review of observations of NSD from recent earthquakes is therefore thought to provide valuable insights about their nature, frequency, severity, and effects on safety and functionality of buildings. Unlike structural damage, collection of NSD data is rare, and there is a lack of standard methods for damage inspection, reporting, and record keeping. This means that data available from different regions differ in terms of details and geographical density. Damage assessment in Italy is reported in the forms for *post-earthquake damage and safety assessment and short-term countermeasures* [Baggio et al. 2002, 2007]. These assessments consider only architectural elements and utilities, and exclude damage to building contents. Moreover, only occurrence of a certain type of damage is reported, without details on their extent. In Portugal, assessment of NSD was performed by inspection of available photographs and through enquires made in the evocation of past century events. In Iceland, insurance against earthquakes is mandatory, and post-earthquake insurance claims and inspection reports prepared by qualified engineers could be used to establish a quantitative dataset of damage, both structural and non-structural. Although the type, nature, and detail of the data collected in these study areas are very different, a consistent theme is maintained by focusing on the most commonly damaged elements in each of the study areas.

2. Identification of the most vulnerable non-structural elements

Non-structural elements include a large variety of items that are commonly classified as architectural elements, building contents and utilities (Table 1). To identify the most commonly damaged NSE, damage data from past earthquakes in the study areas were analyzed in detail, and the results are presented in the following sections.

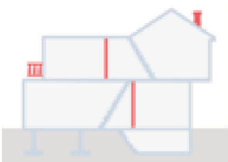
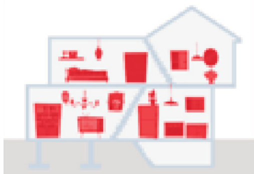
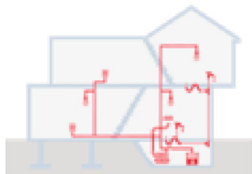
Architectural elements	Building contents	Mechanical, electrical, and plumbing (MEP) elements
		
• Partitions, • ceilings, • storefronts, • glazing, • double-skin façade • cladding, • veneers, • chimney (< 6m), • architectural ornamentation, • stairways.	Furniture, Fixtures and Equipment: • shelving and book cases, • industrial storage racks, • retail merchandise, • books, • medical records, • computers and desktop equipment, • wall and ceiling mounted TVs and monitors, • file cabinets, • kitchen, machine shop or other specialty equipment, • industrial chemicals or hazardous materials • museum artifacts and collectibles.	• Pumps, • chillers, • fans, • air handling units, • motor control centers, • distribution panels, • transformers, • distribution systems including piping, ductwork and conduit, • radiators. Exterior elements: • Fences, • emergency doors.

Table 1. Examples of non-structural elements.

2.1 The Italian case: Mt. Etna pilot area

Recent earthquakes in Italy have highlighted the risk due to NSD. The study area considered in this work, Mount Etna in Sicily, experiences frequent small to moderate earthquakes which cause NSD. Identification of most vulnerable NSE in this region is based on a quantitative analysis of damage collected in the region, as well as a qualitative inspection of photographic documentation (see Annex 1).
The quantitative assessment was supplemented with a new study that aims to correlate NSD to overall building damage. Such correlation allows to assess NSD directly from the classification of damage level within the EMS-98 classes [Grünthal, 1998], i.e. D1 to D5.

2.1.1 Quantitative analysis of damage data

Data collected by the local Civil Protection Agency (DPCR) and reported in post-earthquake damage and safety assessment and short-term countermeasures (AeDES form) was used for this analysis. These forms contain some information relevant to structural and NSD (Figure 1). For example, Section 4 contains information on the level and the extent of structural damage to specific components (vertical and horizontal structures, roof, etc.), which are further quantified by the fractions of observed damage. Similarly, Section 5 of the form contains information on the occurrence of damage to NSE and specifically to some architectural elements and utilities. However, infills and partitions in this form are meant to represent structural elements.

Damage level - extension / Structural component Pre-existing damage	DAMAGE (1)									
	D4-D5 Very Heavy			D2-D3 Medium-Severe			D1 Light			Null
	> 2/3	1/3 - 2/3	< 1/3	> 2/3	1/3 - 2/3	< 1/3	> 2/3	1/3 - 2/3	< 1/3	
	A	B	C	D	E	F	G	H	I	L
1 Vertical structures	□	□	□	□	□	□	□	□	□	○
2 Floors	□	□	□	□	□	□	□	□	□	○
3 Stairs	□	□	□	□	□	□	□	□	□	○
4 Roof	□	□	□	□	□	□	□	□	□	○
5 Infills and partitions	□	□	□	□	□	□	□	□	□	○
6 Pre-existing damage	□	□	□	□	□	□	□	□	□	○

Damage	PRESENT
	A
1 Falling of plaster, coverings, false-ceilings	○
2 Falling of tiles, chimneys...	○
3 Falling of eaves, parapets,...	○
4 Falling of other internal or external objects	○
5 Damage to hydraulic or sewage systems	○
6 Damage to electric or gas systems	○

Figure 1. AeDES form [Baggio et al., 2007]: Section 4 - damage to structural elements quantified with their extension, top; Section 5 - damage to NSE as check list items, bottom.

The final damage class of a building is then assigned according to the criteria proposed by Dolce et al. [2017a, 2017b]:

- Assignment of a synthetic *damage level* for each of the five structural components (vertical and horizontal structures, stairs, roof, infill-partition) by the determination of a univocal damage level which can vary between 0 and 5. The damage level d_i depends on its degree and extent (see Dolce et al., 2017), as reported in Section 4 of AeDES form.
- The *global damage index of the structure* is a weighted sum of damage levels to the five components of the structure, where the weighing factors are different for Masonry (M.) and Reinforced Concrete (RC) structures:

$D_{TOT} = \Sigma_i \, d_i * p_i$ with: i=1-5; and p_i are the component weights, as defined in Table 2.

Components	Weights Masonry-Mixed	Weights R.C. and others
Vertical components	0.6	0.5
Horizontal components	0.2	0.1
Stairs	0.05	0.05
Roof	0.1	0.05
Partitions walls	0.05	0.3

Table 2. p_i weights of different components of a building in assessing the overall damage as defined in the EMS98 classes.

The global damage index of the building D_{TOT} ranges from 0 and 5, and a damage grade of D0, D1, D2, D3, D4, or D5 are assigned according to equidistance ranges in the index definition interval. Although infills and partitions are structural elements in masonry buildings and NSE in reinforced concrete, in the AEDES form they are always considered to be structural elements. This problem is partially overcome by giving them different weights in masonry and concrete (Table 2).

A retrospective analysis of the AeDES forms was performed to extrapolate relationships between NSD and typology of the considered building stock. Data collected by the local department of Civil Protection [Torrisi, 2018] after the typical volcano-tectonic earthquakes located in the eastern flank of Mt. Etna: October 29, 2002 (three events: M_L 4.5, M_L 4.1, M_L 3.9); December 2, 2002 (M_L 3.2); April 20, 2008 (M_L 3.2), were used.

The data sample considered in the analysis consists of 5136 buildings, spread over 23 municipalities (Figure 2), and 7781 NSD occurrences. These buildings are significant for the selected pilot area since they represent traditional housing and related furnishing.

2.1.2 Classification of structural and non-structural damage

Figure 3a shows the distribution of the global damage index of the structures in the study area. Thirty five (35%) of the 5136 surveyed buildings are Reinforced Concrete (RC) structures while the remaining 65% are Masonry/Mixed structures. The percentages in Figure 3b describe the distribution of damage classes inferred from the 5136 AeDES forms (3333 of which are for masonry and 1803 are for reinforced concrete buildings). There are few structures with damage level higher than D3, which is expected for such small events. Less frequent and severe structural damage for this relatively low shaking, helps us to infer that most of the damage was non-structural.

Figure 3c describes the data in terms of final damage grades. Damage class D1 has the highest frequency (74%), while only 8% of the buildings are undamaged. There is a clear distinction in damage classes D0 and D1: for reinforced concrete is around 35% and for masonry buildings is around 65%, almost the double. In all the damage classes the masonry buildings have higher damage frequency.

Figure 2. Map showing the location of the surveyed buildings (red dots) with AeDES forms collected after the 2002 and 2008 earthquakes in the Mt. Etna pilot area. The epicentres of the events selected for the analysis are marked by yellow stars.

Section 5 of AeDES form contains information on NSD to some common components. NSD was reported in 7781 houses, while structural damage was reported in 5136 houses. Of these 7781 reports of NSD, 32% come from RC buildings, and the rest from masonry or mixed ones (see Figure 4a).

Figure 4b shows the distribution of different types of NSD. The most frequent is the type N. 1 (falling of plaster, coverings, and false ceilings. The next frequent NSDs are N. 4 (falling of other internal or external objects) followed by N. 2 (falling of tiles/chimneys).

Damage typologies N. 1 and N. 4 are roughly equally frequent in RC and masonry structures. Damage typologies N.2 and N. 3 (falling of eaves and parapets) are more frequent in masonry structures.

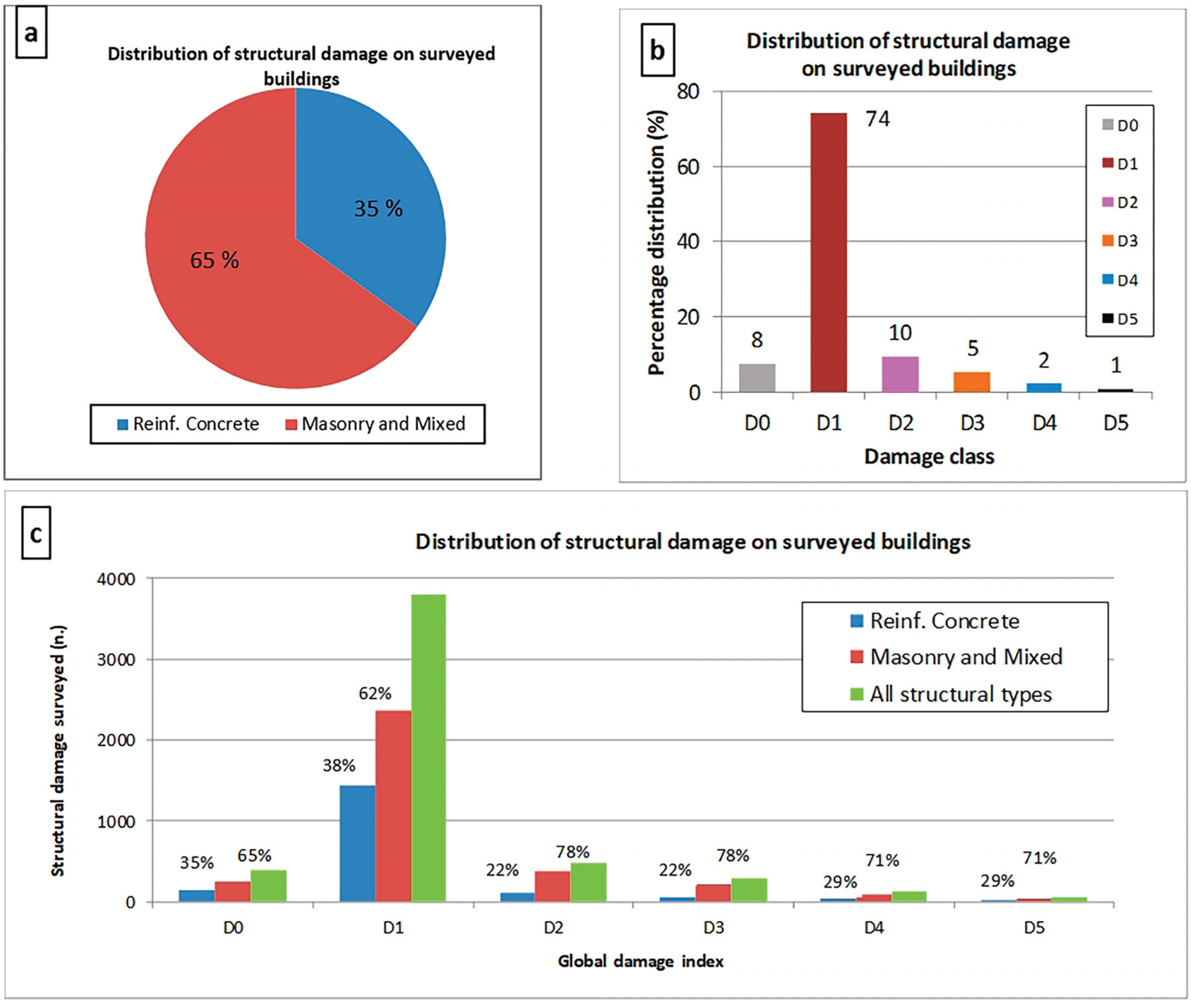


Figure 3. Distribution of damage classes inferred from AeDES forms (a) relative distribution of reinforced concrete and masonry buildings in the survey data; (b) percentage (also expressed in terms of total number of surveyed buildings) distribution of different damage classes; (c): distribution of buildings in different damage classes segregated into masonry and RC types. The classification is based on the EMS-98 scale.

It was attempted to derive relationships between distribution of structural and non-structural damage, vulnerability and ground motion that could be transformed into new fragility curves. This could be an added value to the communication action in terms of preventative measures that could be undertaken.

The results show that distributions of damage to NSE and EMS-98 structural damage classes (Figure 3) have a similar trend: the highest frequency is in class D1 and some differences in D3, D4 and D5 classes (Figure 5). These differences are due to the higher frequency of NSD in masonry buildings for damage classes above D2 (81% vs 78% for D3; 76% vs 71% for D4 and 74% vs 71% for D5).

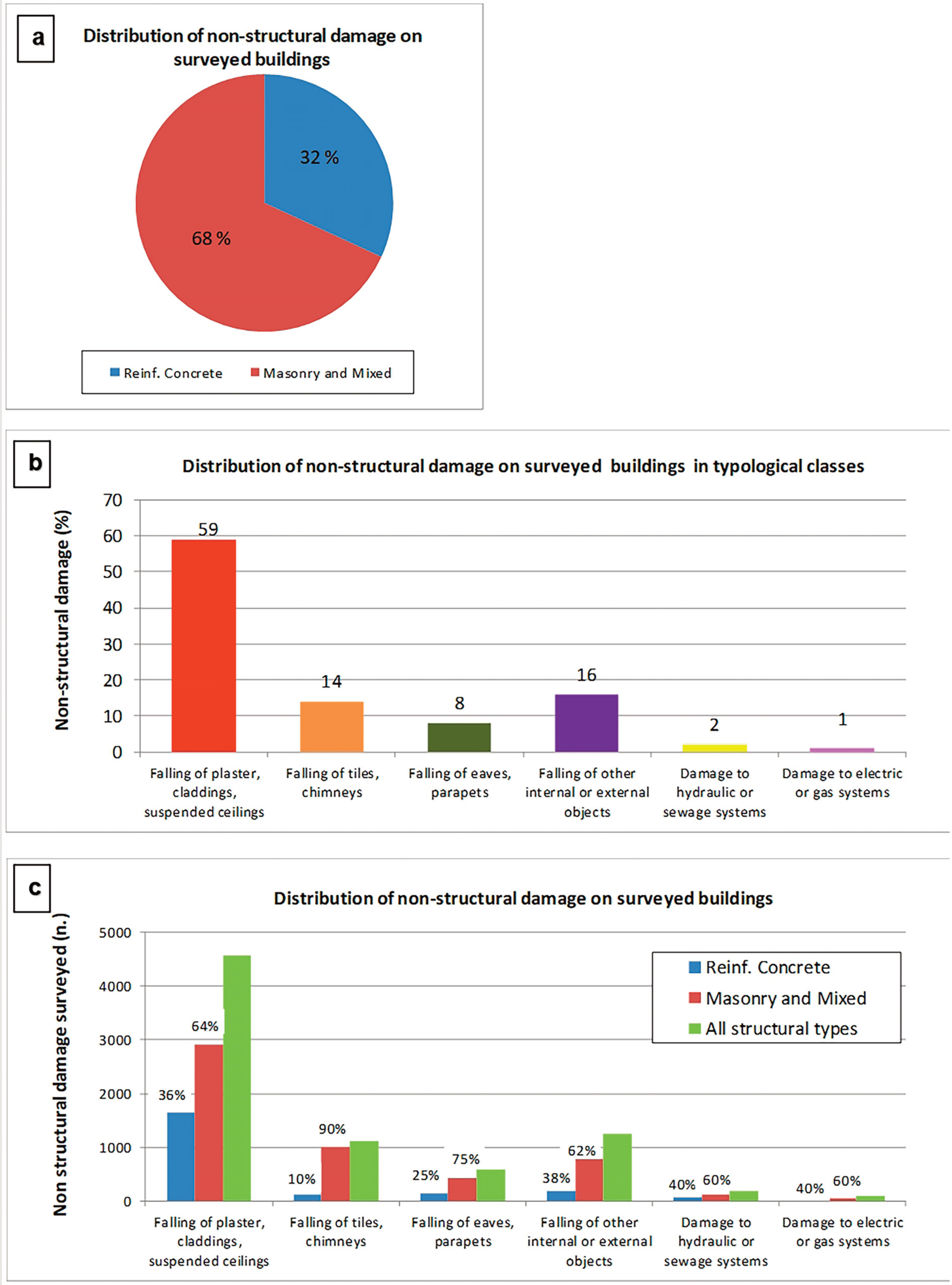


Figure 4. Distribution of damage data on NSE. (a): relative percentages of building types where damage was recorded (b): relative percentage (also expressed in terms of total number of surveyed buildings) of different damage types (c): NSD distribution for each damage typology (expressed in terms of total number of surveyed buildings); relative percentage of masonry and RC buildings for each NSD is plotted.

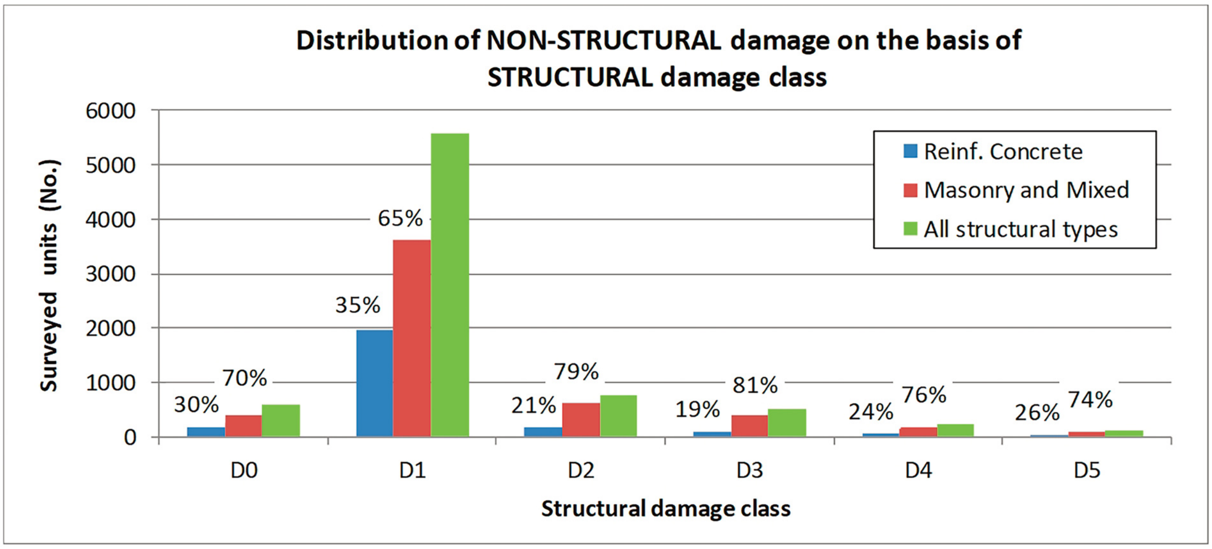


Figure 5. Distribution (expressed in terms of number of surveyed buildings) of NSD for different structural damage classes. Percentage of masonry and RC buildings for each damage class is plotted.

2.1.3 Most common non-structural damage in Mt. Etna area

Figure 6 shows the distribution of NSD types classified by overall building damage class. Most vulnerable NSE can be identified from these results, which lead to the following observations:

• Falling of plaster, claddings, suspended ceilings:
it is the most frequent NSD for both structural types damaged to different levels. Frequency of this type of NSD seems to be approximately the same for all damage classes, except for the most severe damage class D5, where the frequency is slightly lower.

• Falling of tiles and chimneys:
it is more frequent in masonry structures and tends to increase with increasing structural damage.

• Falling of eaves/parapets:
it is not as frequent as the previous cases, although observed.

• Falling of other internal or external objects:
it is the second most frequent NSD, and it seems independent of building type and overall damage class. This damage typology covers different external objects on the façades that are peculiar to local architecture.

• Damage to systems (hydraulic, sewage, electrical and gas):
it was observed but with low frequency with no clear distinction between RC and masonry structures. Although no clear trend was observed with overall damage class, it was the most damage type at damage class 5. It seems that this type of damage increases with increasing structural damage.

2.2 The Portuguese case study: the 1969 and 1998 earthquakes

Analysis of NSD in the Portuguese case study is based on the information collected from two earthquakes : one that occurred in 1969 (affecting the mainland territory) and the other in 1998 (affecting Azores).

2.2.1 Non-structural damage due to the 1969 earthquake

The M_S7.9 earthquake (located 190 km off the cost of Portugal) was the third largest recorded event in national territory, and caused 29 fatalities (16 in Portugal, 8 in Morocco and 5 in Spain). In Portugal, 3 deaths were directly

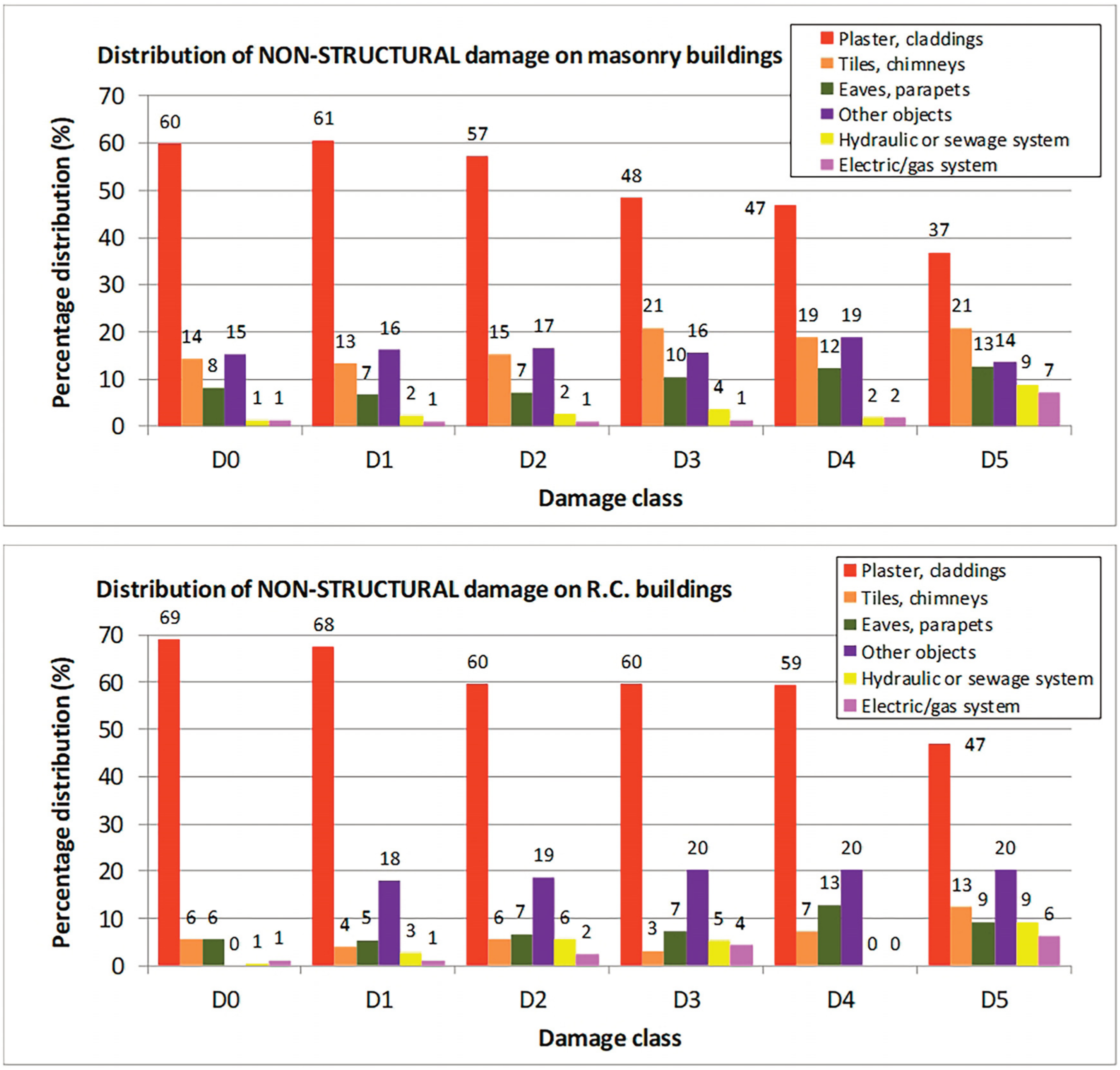


Figure 6. Distribution of different types of NSD for buildings falling under different damage classes (also expressed in terms of number of surveyed buildings) for reinforced concrete (top) and masonry (bottom).

caused by building damages and rock falls [República 02/03/1969; Diário de Notícias 01/03/1969; Diário Popular 12/03/1969] and 13 deaths were due to indirect causes such as panic or heart failure. In south of Portugal, most of the damage was caused in typically vulnerable buildings, e.g. unreinforced masonry structures, adobe rural houses, wood-frame floors and roof, and also in some historic monuments such as churches. In a total of 185 damaged buildings, 20 were moderate to severely damaged. These damaged structures are traditional masonry constructions with thick walls and heavy vaults. Some of these monumental structures had been strengthened with lateral buttresses, and possibly metal or wooden braces.

For reinforced concrete constructions, which at the time, were recently being introduced, structural damage was practically negligible, with the exception of a few cases of clear lack of care in construction. The national electrical network was affected, and it took minutes to one hour to get back into operation; the telephone network was also disrupted for a while.

In the City of Lisbon, 325 km away from the rupturing fault, significant damages were observed. Some chimneys collapsed, walls cracked, tiles fell and many windows and glass panels cracked, and internal walls in older structures collapsed. As shown in Figure 7 (right) collapsed chimneys destroyed vehicles in the city's arteries. We can conclude that the event caused substantial non-structural and content losses according to:

i) the data obtained from notes appearing in national newspapers as published at the time (Figure 7);
ii) the Fire Brigade data (2500 cases; Figure 8 and Annex 2) reported during the first month after the event [Oliveira, 1982];
iii) the testimonials from people who experienced the earthquake (a post event survey is being conducted to collect data on the entire population 50 years after the event at http://sismo1969.ipma.pt/).

1-3-1969 JORNAL DE NOTICIAS PAGINA 3

MILHARES DE CARROS FUGIRAM DE LISBOA TRANSPORTANDO GENTE EM TRAJES MENORES

SÃO ÀS CENTENAS OS PRÉDIOS DANIFICADOS

POR NÃO OFERECER CONDIÇÕES DE SEGURANCA

QUASE TRÊS CENTENAS DE DOENTES EVACUADOS DO HOSPITAL DE S. JOSÉ

Figure 7. Archival information about the 1969 earthquake. Left: Roof collapse of the ice factory (in RC) located at Travessa da Madalena in Faro, ("O Século Ilustrado" March 8, 1969). Right: Car damaged by falling chimneys (Hemeroteca, Digital newspaper archive)

Larger monuments and buildings were also affected. For example, some walls of the the Luz Church cracked. Head of statues in the Navy Ministry Building (Praça do Comércio) and the Loreto Church (Chiado) fell to the ground. The São José Hospital sustained non-structural damage to roof and interior walls, and part of the hospital had to be evacuated.

Even in remote areas such as Guarda city (north of Portugal), the earthquake caused minor structural/non-structural damages that only many years later were attributed to the 1969 earthquake vibration.

Three months after the earthquake, about 150 cases were reported with requests for intervention/restoration of the damage caused by the mainshock, the aftershocks, and possibly the heavy rainfalls that caused landslides and damp patches on some walls.

Figure 8 reports the damage inflicted, in Lisbon, during the 1969 earthquake according to the Fire Headquarter's files, as recorded on the first month after the event [Oliveira, 1982]. In the following months, an average of 70 cases/month were reported. Even ten years later, some accounts of damage were still being reported. It was found that 1.8% of the total received calls reporting damage due to the earthquake were false [Oliveira, 1982].

Figure 9 shows the damage distribution in Lisbon downtown based on data in Annex 2.

For many years, the 1969 earthquake was considered a minor event and, only when the 50th anniversary was approaching (in 2019), new research was initiated. Besides what was described above, new data collection and processing is underway. The data is being collected by survey questionnaires. More than 3600 answers throughout the country have been gathered to have a better understanding of the NSD Among these we should point out to a revision of intensity (EMS-98) evaluations through Portugal, Spain and Morocco, the initiation of several studies on wave propagation and vulnerability of buildings and monuments which suffer some kind of structural and non-structural damage. In the near future better knowledge will be available, which will help understanding the complex seismotectonics of the region.

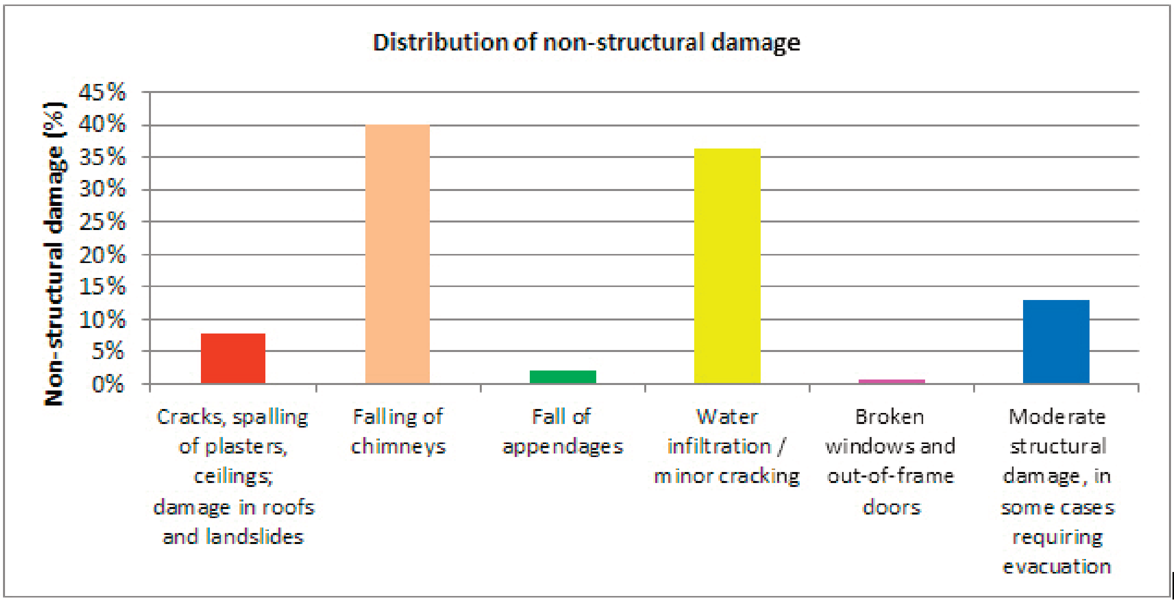


Figure 8. Typical NSD inflicted in Lisbon.

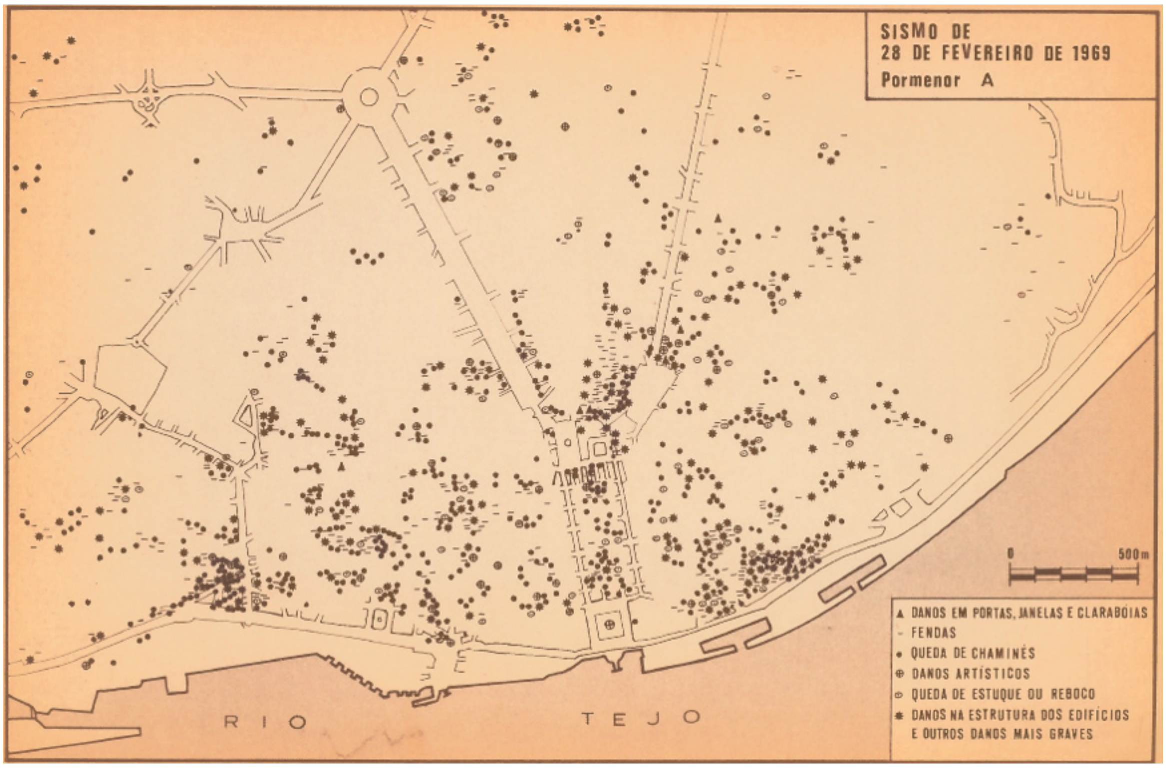


Figure 9. Typical damage to non-structural elements - Lisbon downtown (detailed info in Annex 2) [Oliveira, 1982].

2.2.2. Non-structural damage after the 1998 Azores earthquake

The July 9, 1998, Mw 6.2 Azores Earthquake struck Faial, Pico and San Jorge islands. It caused 8 deaths, hundreds of injuries, and left 2500 homeless. Thirty-five and ten percent of the building stocks in Faial and Pico respectively, were severely damaged resulting in significant socioeconomic impact for a long period. The most widely used type of construction in these islands, a "traditional construction" consisting of stone masonry exterior walls, timber partition walls and roof, is highly vulnerable to earthquakes. Table 3 shows the catalogued construction types: traditional construction (TC), altered traditional building (ATC), current construction (CC) and mixed construction (MC). Figure 10 presents the distribution of damage grade along the periphery of Faial Island. With this information of the building stock, it was possible to correlate the damage types for each construction system (Figure 11 a) and b), as well as understand the overall structural behaviour of each building type [Neves et al., 2012].

Type	Vertical structure	Floor type	Roof type
TC - Traditional construction	Stone masonry	Timber	Timber truss
ATC - Altered traditional construction	Stone masonry	RC (slabs in kitchen and WC)	Timber truss
CC - Current construction	Reinforced concrete (RC)	RC slabs	RC or timber
MC1 - Mixed construction 1	Stone masonry stone	RC slabs	Timber truss
MC2 - Mixed construction 2	RC and stone masonry	Timber and RC slabs	Timber truss
MC3 - Mixed construction 3	RC	RC slabs	RC or Timber truss

Table 3. Types of constructive system [Neves et al., 2012].

A post-earthquake survey named "Auto de Vistoria" was carried out in 1998 to gather information regarding the damage sustained by each building and the economic situation of the family living there. This information was collected to help in post-quake reconstruction and rehabilitation process. Unfortunately, this survey has a lack of information regarding:

- damage observed to structural and non-structural elements;
- damage that might have occurred prior to the earthquake and thus not associated with it;
- the percentage of buildings affected to each damage grade (D1 to D5). Details of damage to different structural components (e.g. vertical elements, floors and roof) and non-structural component (infills and partitions) were missing.

In 2007, a repository of photographs was collected, which became an important source of information for researchers [Neves et al., 2008]. In recent investigations, a total of 3909 damaged buildings were geo-located and the dataset containing exterior house photographs and damage descriptions included in "Auto de Vistoria" dataset, were analysed case by case to identify specific types of damages [Ferreira, 2008]. Taking advantage of the AeDES field manual [Baggio et al., 2007], it was possible to establish a structural and non-structural building damage classification in terms of the European Macroseismic Scale 1998 (EMS-98).

As shown in Figure 11 c) more than 40% of the Faial and Pico building stock suffered substantial non-structural and content losses (D2-D3, associated mainly to D2 and D3 damage classes).

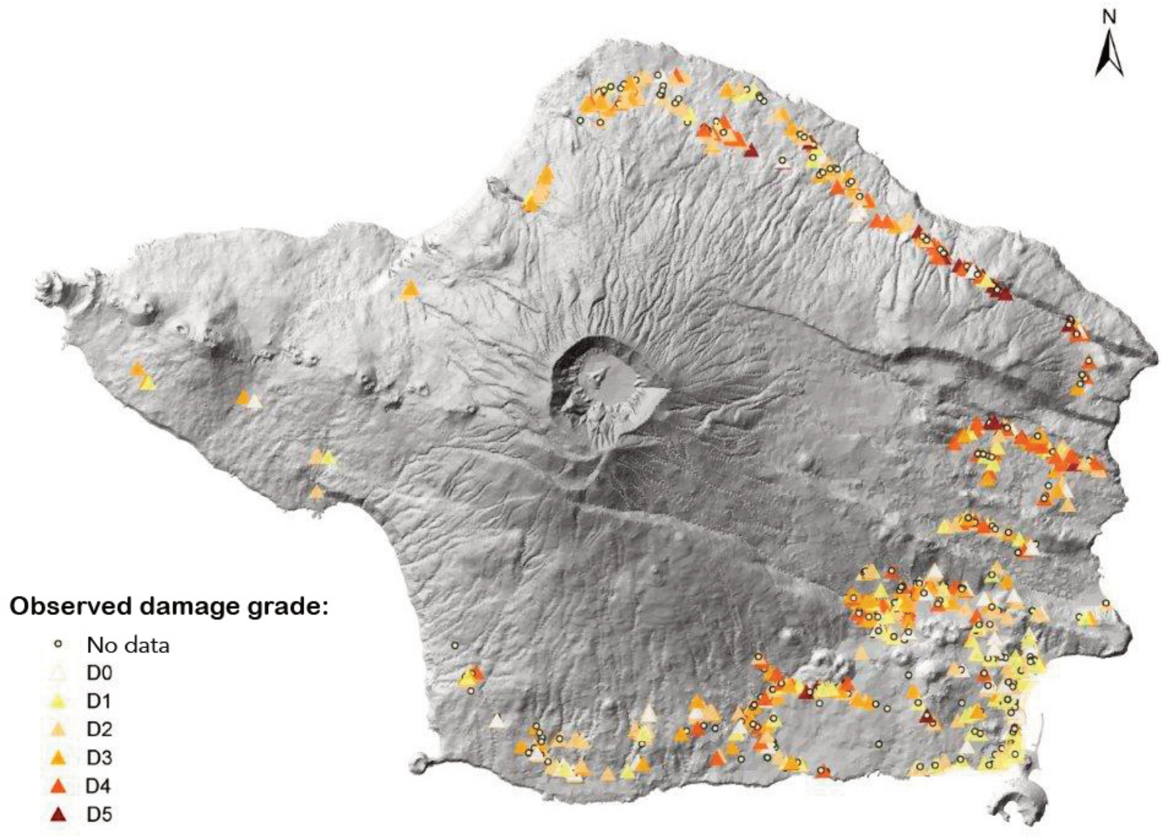


Figure 10. Distribution of damage grade in Faial, 1998 earthquake [Oliveira et al., 2008].

In the framework of the KnowRISK EU project, the 1998 earthquake dataset (photos and damage descriptions contained in "Auto de Vistoria" dataset) was analysed in detail in order to collect and identify common damage to non-structural elements and contents (Figure 12) such as:

- interior fixtures, including kitchen and bathrooms (for example, lack of latches to prevent cabinet doors from opening);
- falling of pieces of plaster;
- cracking and overturning of roof chimneys;
- damage to exterior walls around windows;
- falling of non-anchored masonry veneer;
- displacement of roof tiles;
- failure of walls and various types of building contents.

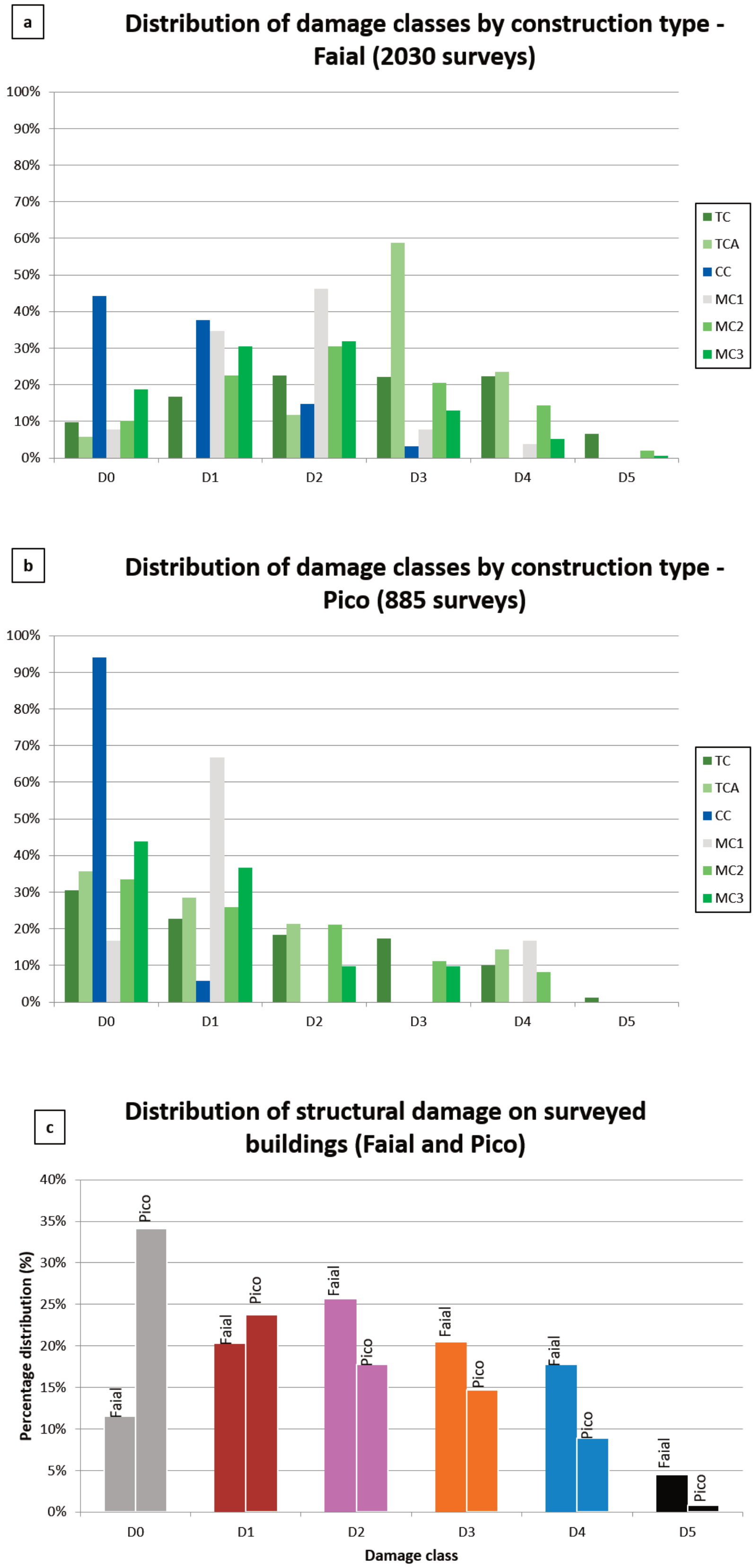


Figure 11. Distribution of damage classes in Faial and Pico: a) Faial: percentage of damaged buildings in each damage class by type; b) Pico: percentage of damaged buildings in each damage class by type; c) percentage of damaged buildings in each damage class (Fail and Pico).

Figure 12. Typical damage to non-structural elements in Azores: a) cabinet doors not latched; b) sliding roof tiles; c) out-of-plan edge walls showing falling cabinets. (Auto de Vistoria post-earthquake survey).

2.3 The Iceland case study

Study on NSD in South Iceland was based on observed damage in three destructive earthquakes: two in June 2000 with M_W 6.5, and one in May 2008 with M_W 6.3 (see Figure 13). The observations are recorded in two different datasets containing details of damage in low-rise residential buildings, which dominate the building stock.
One of the datasets is a collection of insurance claims, called hereafter as quantitative dataset. It covers losses to structural and non-structural elements excluding building contents. Several analyses of the dataset have been reported in the literature [Bessason et al., 2012, 2014, 2020; Bessason and Bjarnason, 2016].
The other dataset is a collection of interviews of residents and photographs of damaged elements collected by the Earthquake Engineering Research Centre (EERC) of University of Iceland. This data, referred to as qualitative dataset, is mainly used to understand vulnerability of household contents and their distribution in different rooms within a house.
The 17th of June 2000 earthquake is referred to as Eq1, the 21st of June as Eq2, and the 29 May 2008 as Eq3 in the following. The insurance claims data allowed classification of losses into sub-categories that helped in identification of types and relative vulnerability of different non-structural elements.

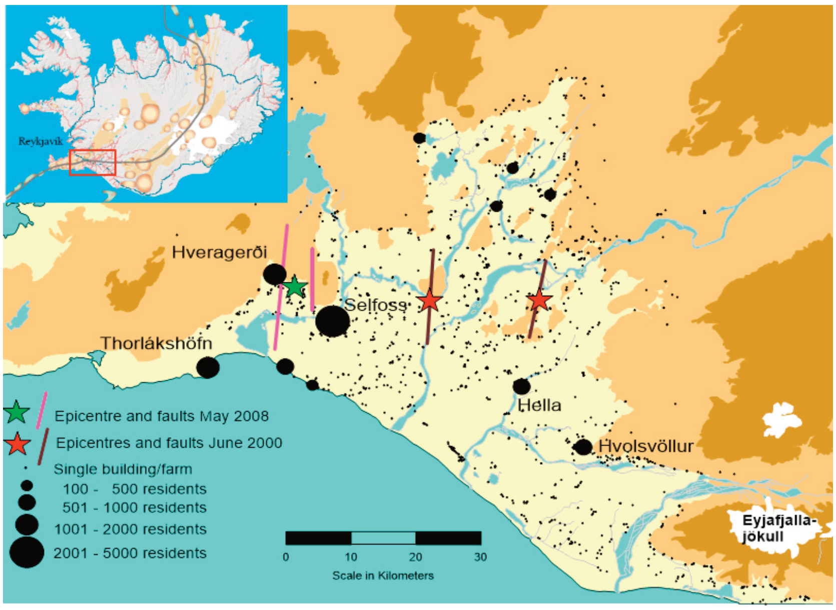


Figure 13. A map of the study area in South Iceland: the stars indicate the epicentres of three recent earthquakes from which damage data is collected; major settlements are indicated by dots with their population indicated in the legend and the smallest dots represent isolated farms or buildings. The inset shows the map of Iceland where the study area is indicated with the red rectangle.

2.3.1. Analysis of most common NSD

Distribution of structural and non-structural damages in the three earthquakes is shown in Figure 14. The figure shows proportions of structural and non-structural damage in reinforced concrete (RC), timber, and masonry buildings. For all buildings which reported loss, non-structural loss was over 60% of the total loss. For timber and RC buildings, which showed better seismic performance than masonry ones, [Bessason and Bjarnason, 2016], non-structural damage was close to 80% of total damage for Eq2 and Eq3. These results clearly show that for moderate to large size earthquakes, which are frequent in the study area, non-structural damage contributes to most of financial loss.

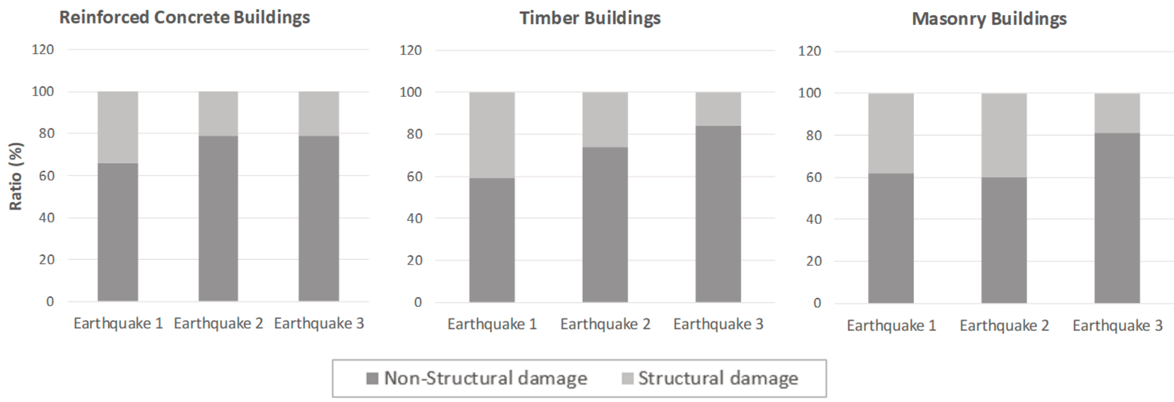


Figure 14. Relative fraction of structural and non-structural (excluding building contents) damage in three buildings typologies inferred from the insurance claims data obtained from three recent earthquakes in South Iceland Lowland.

A better understanding of the most-vulnerable NSE can be obtained by classification of loss into different categories. Loss data from Eq3 is available with more details which allow for grouping into more classes than the data from Eq1 and Eq2 [see Bessason et al., 2012 for more details]. For comparing the dataset from these different events, a simple classification as shown in Table 3 can be used.

Class	Description
1	Interior finishing work (partition walls, mortar, suspended ceilings, cladding)
2	2.1 Interior fixtures, incl. kitchen and bathrooms, doors, flooring, wall tiles, etc. 2.2 Windows, glass, exterior doors, wall cladding 2.3 Paintwork outdoors and indoors, including crack filling and surface treatment
3	Plumbing (cold water, hot water and sewer pipes), radiators, electrical installations

Table 4. Classification of non-structural damage observed during three recent earthquakes in South Iceland Lowland.

Relative proportions of different categories of loss recorded in reinforced concrete (RC), timber, and masonry buildings are shown in Figure 15. In all building types, and all the three earthquakes, category 2 (see Table4) loss dominates the total non-structural loss. Since category 2 contains a lot of different types of loss, it is useful to subdivide this into sub-categories, which is possible for the data from Eq3. These sub-categories are as indicated in Table2. The relative proportions of different sub-categories within category 2 losses are shown in Figure 16. Sub-categories 2.1 and 2.3 dominate the loss in category 2, which in turn dominates total non-structural loss.

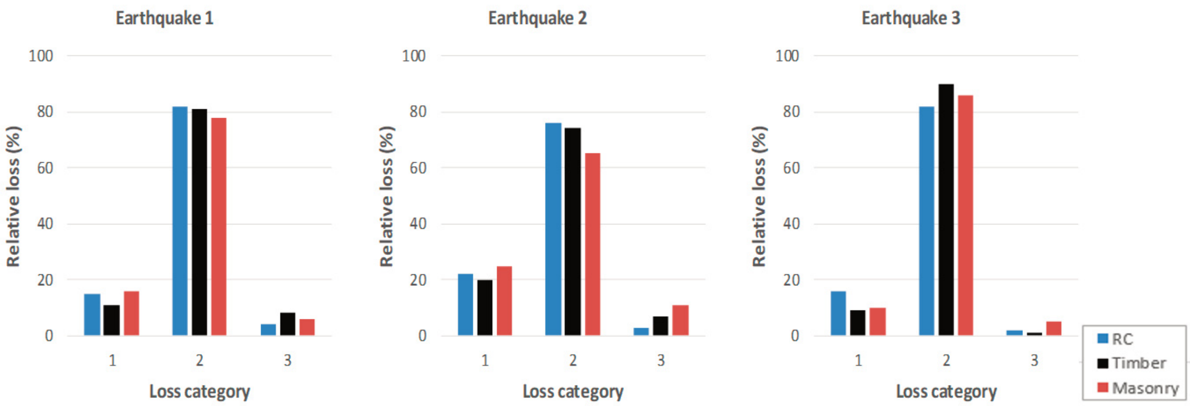


Figure 15. Relative proportions of different categories of non-structural loss document in the three recent earthquakes in South Iceland.

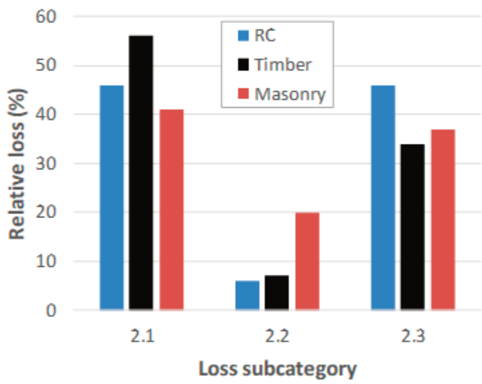


Figure 16. Relative proportions of different sub-categories of non-structural loss category 2 document in the May 2008 earthquake in South Iceland.

Windows, glass, exterior doors, and wall cladding seem to be more vulnerable in masonry buildings, which is probably because they are structurally more vulnerable.

Detailed analysis of qualitative dataset [see Thorvaldstottir and Bessason, 2018] provided important insights on the vulnerability of household items. The analysis was based on study of different rooms of a building, different types of movements of the objects therein, and different mitigation measures required to prevent losses. A more thorough treatment of the analysis is presented in a separate paper in this issue [Thorvaldsdottir et al., this issue]. The results in Figure 17 show that most of the damage and disruption occurs in the kitchen. In total, 41 vulnerable items were identified in the kitchen, of which simple actions such as ‘move’, ‘protect’, and ‘secure’ could prevent loss to 17, 12, and 6, items, respectively. In bedrooms and offices, these actions could prevent loss to 9, 19, and 5, items, respectively. In total 44, 32, and 84 items were identified on which losses could be prevented by ‘move’, ‘protect’, and ‘secure’ actions. However, items and situation for which no obvious and simple mitigation measures could be identified were also found.

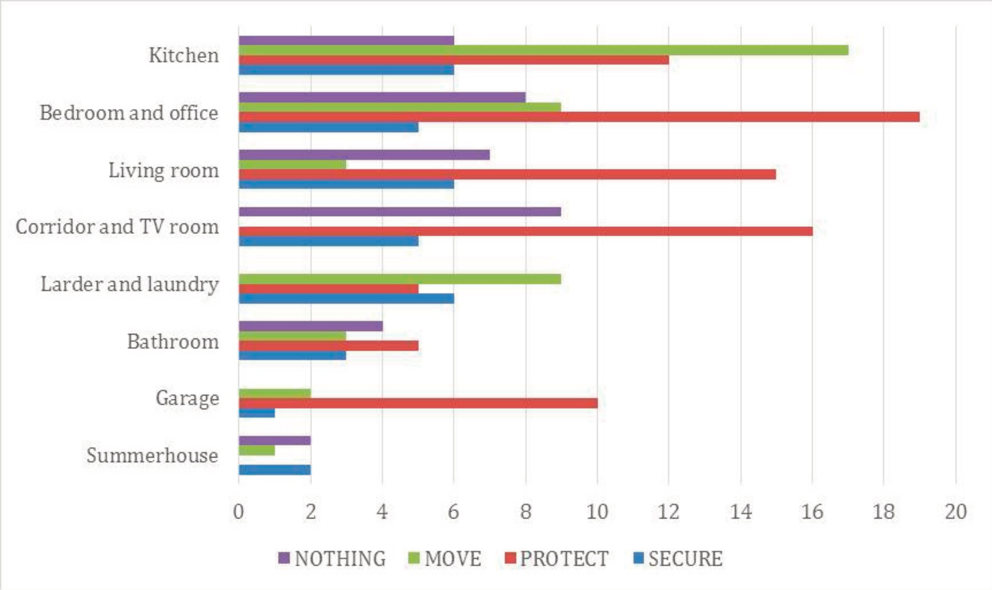


Figure 17. Mitigation type frequency in each room type [Thorvaldsdottir et al. 2020].

2.3.2. Most common non-structural damage in Iceland

The results from the analysis are summarized as follows:

- Non-structural loss contributed to around 80% of all financial loss in three recent moderate earthquakes in Iceland.
- Interior fixtures, flooring, wall tiles, paintwork, crack filling and surface treatment dominated the loss.
- Most of the damage and disruption occurred in the kitchen where 41 vulnerable items were identified. Simple actions of 'move', 'protect', and 'secure' could prevent damage to 17, 12, and 6 of these items, respectively. It total, 44, 32 and 84 items could be made less vulnerable by 'move', 'protect', and 'secure', actions, respectively.
- From the observations reported above and results presented, in terms of future mitigation actions, the most frequent action that could prevent the observed damage is in preventing free standing objects from moving. The next most frequent is preventing of cabinet doors from opening, for example by using special locks.

2.4 Most commonly damaged elements in the three pilot areas

As a summary, the most vulnerable NSE in the three study areas is presented in Table 5. All these items can be severely damaged during an earthquake creating a life-safety hazard. If anchorage, bracing or other solutions to resist seismic forces are non-existent, mitigation is necessary to achieve the selected performance level. These solutions are discussed in a separate paper in this issue [Solarino et al., this issue].

3. Discussion and conclusions

The present study is a review of the most common damage to non-structural elements (NSE) caused by recent earthquakes in the pilot areas of three seismically active countries. Non-structural damage (NSD) dominated total loss in these case studies, which is often the case when the shaking is moderate to low or structures are highly resistant to earthquakes as in the case in Iceland. The compiled data and their analysis provide an important insight on the vulnerability of various NSE. These insights are important in designing prevention strategies and communication to the stakeholders, which is discussed in a separate paper [Solarino et al., this issue]. As post-earthquake damage surveys typically focus on structural damage, a purely quantitative analysis, for example for calibration of fragility curves of NSE, is challenging in many situations. Since post-earthquake surveys are more

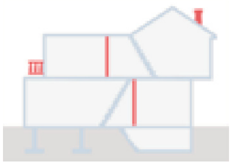
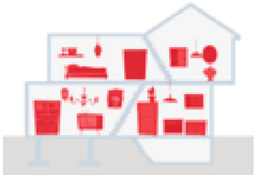
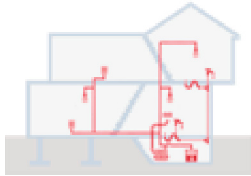
Architectural elements	Building contents	Mechanical, electrical, and plumbing (MEP) elements
		
Typical NSD observed in Italy: Partition walls, plaster, cladding, suspended ceilings, tiles, chimneys, eaves/parapets, architectural ornamentation (internal or external objects).	Typical NSD observed in Italy: No data.	Typical NSD observed in Italy: Electric or gas system, hydraulic or sewage system.
Typical NSD observed in Portugal: Partition walls, cladding, tiles, chimneys, glazing, masonry veneers (Azores).	Typical NSD observed in Portugal: Kitchen cabinets, doors.	Typical NSD observed in Iceland: Electric system.
Typical NSD observed in Iceland: Partition walls, mortar, suspended ceilings, cladding, glazing, wall tiles, floor tiles.	Typical NSD observed in Iceland: Interior fixtures (kitchen and bathrooms), doors.	Typical NSD observed in Iceland: Plumbing (cold water, hot water and sewer pipes), radiators, electrical installations.

Table 5. Non-structural damages observed in the three case studies.

concerned with safety and needs assessment in terms of major structural elements, they tend to overlook the risks imposed by NSE. In addition, collection of NSD data can be time consuming and tedious because the inventory of items to be dealt with is large. Good example of customized forms for NSE and NSD is given in the ITERATE EU project (http://www.iterate-eu.org/wp-content/uploads/2018/12/DE3-NonStructural-Elements.pdf).
However, given the importance of mitigating NSD and improving societal resilience to earthquakes, it is important to understand potential risk and plan mitigation measures. At the engineering and technical levels, this requires proper models of vulnerability and exposure data through which risk can be quantified by integrating with the hazard. One potential way in which this can be achieved is through empirical data, which become available after an earthquake. It is therefore necessary to start collecting systematic data on NSD after earthquakes.
Apart from financial loss, NSD have another equally important dimension, which is the disruption and potential injury or even fatality they can cause on building occupants. While more accurate understanding of prevalent risk is under study, it is equally important for the society and the general population to understand the type and severity of expected NSD and their potential mitigation measures. Through such awareness of risk and available mitigation measures, NSD can be mitigated to some extent. This requires percolation of scientific knowledge in this field, mainly gathered in the form of empirical data, to be translated and summarized in the form and content that is most suitable for general people. Even though modern seismic design codes have some provisions for limiting NSD, prevention of damage to building contents and their consequences such as disruption, injury, or casualty, need to be mitigated by stakeholders such as building owners and occupants. Stakeholders will be more motivated to take mitigation measures if they are aware of potential risk, feasible mitigation measures and their costs/benefits. Information on non-structural elements during past earthquakes, like the one presented in this study is useful in identifying mitigation priorities and communicating them to the stakeholders. This study addressed this important issue at three different study areas with different seismotectonic and socio-economic background and with different levels of details in available data.
In the Italian and Portuguese pilot areas, architectural elements (in the inner but also outside) of households are found to be the most vulnerable. These include plasters, other surface coverings, and false ceilings. External ornamental architectural elements are found to be the second most vulnerable NSE in these areas. Buildings in Iceland are very different than those in Italy and Portugal, both structurally and architecturally. Most of the buildings

are low to medium heights and are designed as stiff structures capable of sustaining high wind. These constructions lack external ornamental elements typically found in Italy and Portugal. Most vulnerable NSE in Iceland were found to be interior fixtures, doors and windows, wall cladding, flooring, paintwork and other surface treatments. Data from the Icelandic case study in terms of building contents shows that most of damage and disruption to contents occurs in the kitchen, and that most of such damages can be mitigated by homeowners through simple measures.
The findings of this study are valuable for two groups of stakeholders. The first group is of engineers, architects and technicians who can use these findings to understand impending vulnerability and modify/improve design and construction systems and materials. The second and equally important group is of homeowners. Awareness of impending risk and mitigation measures will help them to become less vulnerable to NSD. This can be achieved through exchange of findings of studies like these in a form and manner that is most receptive to the general population. This points to the need for proper tools and protocols for communication of NSD risk to the general population. These important needs and their solutions are presented in companion papers in this issue.

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