Comprehensive damage analysis of buildings affected by the 2008 South Iceland earthquake

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SUMMARY:
South Iceland is an active seismic zone. In May 2008 a M_w6.3 earthquake struck the Ölfus region in South Iceland. The recorded maximum PGA was 0.88g. A great deal of damage occurred but fortunately there was no loss of life. All buildings in Iceland are registered in a detailed official database. Insurance against natural disasters is obligatory. After the Ölfus earthquake, repair and replacement cost for every affected building was estimated in order to cover insurance obligations. This work was performed by trained estimators. To have an opportunity to analyse the field observations, the damage data for every property was split into number of subcategories and stored in an electronic database. Study of the data has shown that the structural damage was very limited. On the other hand. it showed that most of the monetary damage was related to flooring, and cosmetic surface damage, that required small repair and paint work.

Keywords: Field data, Vulnerability, Damage statistics, Low-rise buildings, Non-structural damage

1. INTRODUCTION

Knowledge of seismic vulnerability of buildings is fundamental when evaluating earthquake risk and expected loss. It is also useful in disaster planning in real time after an earthquake, when studying consequences of different earthquake scenarios, and in planning of mitigation and retrofit programs. Vulnerability of buildings depend on many things like building traditions, building type, material, structural form, regularity in plan and elevation, detailing, quality of seismic codes and seismic design, design supervision, workmanship and inspection. These factors can be country, regional or area-depended, although many similarities can often be found between locations. Earthquake loads are known to by very site-specific and depend on regional seismicity, fault mechanism, attenuation characteristic, topography, soil conditions etc. It is therefore important, whenever possible, to carry out site-specific post-earthquake damage studies in order to learn from earthquakes and construct country based or regional-dependent seismic vulnerability relationships of buildings.

Most of the existing Icelandic building stock is built as in-situ-cast reinforced concrete buildings, in which the lateral load-bearing system is dominated by structural walls with inherent lateral resistance. In rural areas and smaller villages, low-rise houses dominate (1-3 stories) the stock. Most buildings are made of reinforced concrete or timber. Typical South-European-type masonry buildings do not exist in the building stock, but during a certain period, mainly from 1940 to 1970, pumice blocks were used. Steel structures are rare and mostly used in industrial buildings and for new farm houses (stables, cowsheds, sheepcotes), but almost never for residential houses.

The seismicity in Iceland is related to the Mid-Atlantic plate boundary which crosses the country. Within Iceland, the boundary shifts eastward through two complex fracture zones. One is located in the South Iceland lowland, called the South Iceland Seismic Zone (SISZ), whilst the other, the Tjörnes Fracture Zone, lies mostly off the northern coast of Iceland. The largest earthquakes in Iceland have occurred within these zones. On the 17^{th} and 21^{st} of June 2000 two earthquakes of magnitude 6.5 (M_w)

struck South Iceland, and on the 29th of May 2008 an 6.3 (M_w) magnitude earthquake shook the area again. The epicentral distances between these quakes were less than 35 km, and they were all shallow with hypocentral depth of less than 7 km. These three events constituted a kind of earthquake sequence that has been observed several times in the past in the South Iceland zone (Einarsson, 1991). These sequences typically occur about every hundred years. Each sequence can consist of 2 to 6 major earthquakes (M_w>6). The last sequence, before the 2000-2008 earthquakes, occurred in 1896, when 5 earthquakes of magnitude greater than six struck the area in two weeks, the 6th one finishing the sequence occurred in 1912.

The largest agricultural region in Iceland is located within the SISZ. Several small towns, schools, medical centres, industrial plants, geothermal and hydropower plants, and some major bridges are in this area. In fact it has the entire infrastructure that characterizes modern society. The population in the region is about 18,600 inhabitants (January 2008), and there are approximately 6,000 residential houses, mostly low-rise buildings. The population is close to 6% of the total population in Iceland.

During the 2000 and 2008 SISZ earthquakes, no residential buildings collapsed. Only a few farm buildings did. However, a considerable number of houses suffered damage, both structural and non-structural. The most common structural damage was fine cracks in walls, tilting and settlement of foundations and bottom slabs. At least 40 houses were judged un-repairable after the June 2000 earthquakes and about 30 after the May 2008 event.

The overall aim of the work presented in this paper was to learn more from the observed damage data after the May 2008 Ölfus earthquake of low-rise residential buildings. The main focus is to report and map the damage in detail, and study how the estimated repair cost is statistically split into different subcategories of structural and non-structural damage. By analysing the main weaknesses of buildings, it is possible to improve design and invoke countermeasures that can mitigate damage in future earthquakes.

A key factor in the damage analysis is to have a detailed and accurate building inventory. Very often such registers are partial and limited, or only available for some towns, regions or single provinces. Much work has therefore to be carried out in order to fill in gaps, combine new and old registers, and make some estimates and assumptions to cover missing data. The data behind this study is so to say based on complete property as well as a comprehensive damage data base. These databases have already been used by the authors of this paper to derive probabilistic vulnerability functions for five types of low-rise concrete, timber and pumice residential buildings for four earthquake intensity levels (Bessason et al. 2012). The functions give the actual damage ratio, defined as estimated repair cost as a proportion of building insurance value (replacement cost). The main focus was on the total damage for each structure, and little effort was made to analyse or categorize the damage.

2. THE ÖLFUS EARTHQUAKE IN MAY 2008

2.1 Earthquake data

On the 29th of May 2008, a strike-slip earthquake struck the South Iceland Seismic Zone. It consisted of two events on separate faults, as shown in Fig. 2.1. It was initiated on the eastern fault and that earthquake triggered another event about one second later on the western fault. A macro-seismic epicentre has been determined at 63.98°N and 21.13°W (Sigbjörnsson et al. 2009). The magnitude of the combined event was estimated as 6.3 (M_w). The earthquake was recorded by the Icelandic Strong motion network (Sigbjörnsson et al. 2009), and in the new small-aperture strong-motion array in Hveragerdi, the so-called ICEARRY (Halldórsson et al. 2009). Selected time histories and response spectra can be found in the ISESD database (Ambraseys et al. 2002). In Hveragerdi the maximum PGA (largest component) was recorded 0.66g in the strong motion network and in Selfoss 0.54g PGA.

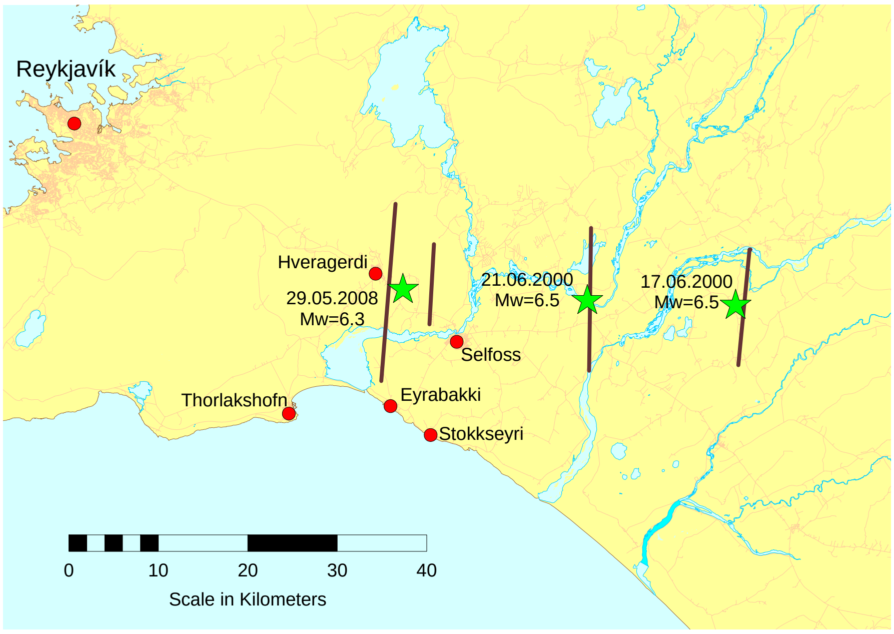

Figure 2.1. A map of the South Iceland lowland showing the two active faults of the 29 May 2008 earthquake and the macro-seismic epicentre between them (green star). The main centres of urbanization in the region are shown with red dots. The epicentres as well as the faults of the two June 2000 earthquakes are also shown.

Values as high as 0.88g were registered at one station in the ICEARRAY system (Halldórsson and Sigbjörnsson 2009). Response spectra from stations located on rock, both in Hveragerdi and Selfoss, exceeded the Eurocode response spectrum (a_{gR}=0,4g). This was the case for both short and long (above 0.6 s) period bands (see Bessason et al. 2012). Regarding the longer periods, they are most likely affected by the near-fault ground-motion (Sommerville et al. 1997). It should be brought to notice that in all three recent Icelandic earthquakes (two from 2000 and one from 2008) of moderate size (M_w6.5, M_w6.5, M_w6.3) a near-fault motion has been observed (Rupakhety et al. 2011). This is of concern regarding structures with long natural periods.

2.2 Ground motion intensity

In order to relate the observed damage to ground motion intensity, an appropriate parameter must be defined. Since most of the houses in South Iceland are low-rise shear wall buildings with a low natural period, it was decided to use the PGA parameter. The PGA at each site was computed by an area-specific attenuation model (Ólafsson, 1999; Ólafsson and Sigbjörnsson, 2002). The model predicts the median value of PGA for both horizontal components. The intensity is grouped into predefined intervals based on increasing the lower and upper bound values by approximately a factor of 2, when going from one intensity level to the next. The levels used are shown in Table 2.1 and correspond to the range of PGA values presented by Wald et al. (1999). For more details of the PGA definition used herein see Bessason et al. (2012).

Table 2.1. Intensity levels defined by the upper and lower bound of computed PGA values.

Intensity level	**1**	**2**	**3**	**4**
PGA – (g)	0.05 – 0.09	0.09 – 0.18	0.18 – 0.34	0.34 – 0.65

3. COMPREHENSIVE DATA BASE

3.1 A comprehensive property register and damage data

All buildings in Iceland are registered with an Id-number in an official property database (Registers Iceland). It covers all properties, building-to-building, from expensive power-plants, hospital and schools and down to stand-alone garages, cowsheds and sheepcotes. The inventory contains detailed information about type of use (residential, school, hospital, farm building, etc.), post and street address, owner, date of construction, floor area and volume, number of stories, main building material, and GPS-coordinates. In addition it contains results of valuation, both for taxation and reconstruction insurance value (replacement value). However no information of the structural bearing system, plan or elevation regularity, or soil and foundation conditions is stored in the register.

Catastrophe insurance of buildings against earthquakes, volcanic eruptions, floods and landslides is mandatory in Iceland. The insurance cover is managed by an official company, the Iceland Catastrophe Insurance. The insurance valuation is based on the replacement cost less depreciation of building materials, age and upkeep. In the wake of a natural disaster, detailed damage information in every damaged estate is recorded, in order to enable compensation for the estimated repair or replacement cost. Most of the damage in the 2000 earthquakes was spread widely over the South Iceland lowland, whereas the damage of the 2008 earthquake was more concentrated in the two small towns Selfoss and Hveragerdi, closest to the epicentre (see Fig. 2.1). Strong motion data was obtained and is available from both these places.

3.2 Building stock

The population in the South Iceland lowland is around 18,600 inhabitants (January 2008). Of those about 14,160 live in the area close to the two faults of the Ölfus earthquake, mostly in the small towns/villages of Selfoss (6,310), Hveragerdi (2,308), Thorlakshöfn (1,548), Eyrabakki (594) and Stokkseyri (513) (see Fig. 2.1). The rest live in rural areas (2,887). Most of the buildings are low-rise single-family villas or town houses. Only very few buildings can be classified as multi-family apartment houses, and of those none is taller than five stories. In this study, damage data for the low-rises houses are only used. Based on the official property database, 45% of these houses are made of reinforced concrete, 48% of wood and 8% of pumice. More detailed description of them can be found in (Bessason et al. 2012). Figure 3.1 shows the age distribution. The oldest houses, which were built before 1940, are mainly timber houses. Between 1940 and 1970 it was common to build concrete buildings as well as some pumice buildings. From 1980 timber buildings have been most common and thereafter concrete buildings. Pumice buildings have practically not been built after 1980.

3.4 Building typology classes

When evaluating the damage after the Ölfus earthquake 2008, all buildings in the South Iceland lowland where classified. For the low-rise residential houses, two classes were chosen for concrete buildings, two for timber buildings and one for pumice buildings. The age of the buildings was used as a practical means to differentiate between classes. A seismic design code was first introduced in Iceland in 1976, and from around 1980 nearly all concrete buildings had reinforcement in all structural supporting systems. It was therefore decided to use the year 1980, to distinguish between age periods of concrete buildings as well as for timber houses. The pumice buildings are relatively few in comparison to the concrete and timber buildings. As they are becoming less and less important over time (see Figure 3.1), the pumice buildings were all categorised in the same class. The classes are labelled: $concrete_{old}$, $concrete_{new}$, $timber_{old}$, $timber_{new}$ and *pumice*. Majority of new buildings built after 1980 are 1-2 stories, while some of the older buildings are up to 3 stories. Shear walls are more or less found in every building, while masonry infill is practically never used. Table 3.1 shows the main characteristic of each building class. Table 3.2 shows the number of buildings in each category.

Table 3.1. Main characteristic of building classes.

Building class	**Construction year**	**Building material**	**Lateral resistance system**	**Foundation soil**	**No of stories**
$Concrete_{old}$	<1980	Reinforced concrete	Shear walls	Rock /firm soil	1-3
$Concrete_{new}$	≥ 1980	Reinforced concrete	Shear walls	Rock /firm soil	1-2
$Timber_{old}$	< 1980	Timber	Shear walls	Rock /firm soil	1-3
$Timber_{new}$	≥ 1980	Timber	Shear walls	Rock /firm soil	1-2
Pumice	All years	Pumice	Shear walls	Rock /firm soil	1-3

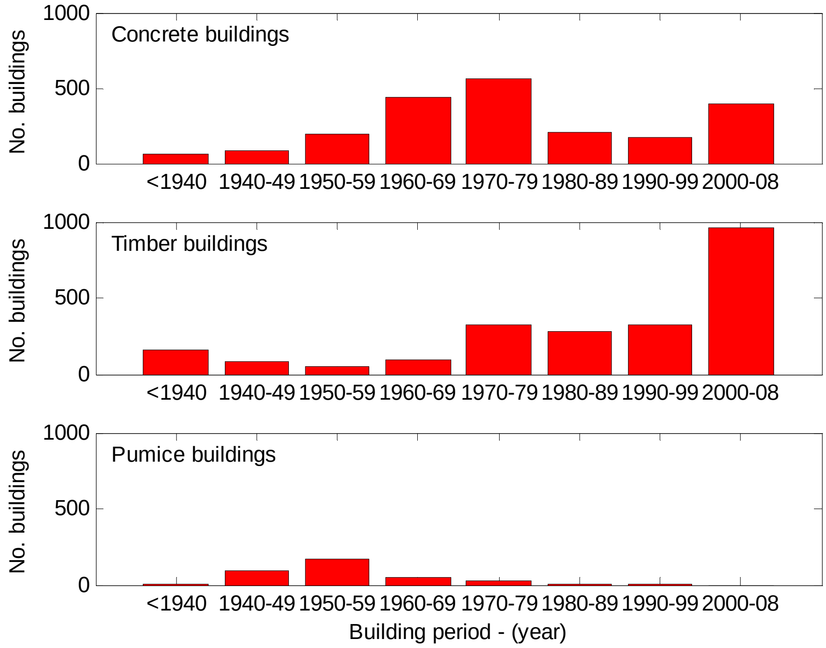

Figure 3.1. Age distribution of low-rise, concrete, timber and pumice buildings, in the Ölfus region.

Table 3.2. Number of buildings in each category in the Ölfus region sorted after ground motion intensity level. .

Building class	**Intensity level**				**Total**
	1 0.05g – 0.09g	2 0.09g – 0.18g	3 0.18g – 0.34g	4 0.34g – 0.65g	
$Concrete_{old}$	106	362	617	252	**1337**
$Concrete_{new}$	26	165	327	260	**778**
$Timber_{old}$	45	250	211	203	**709**
$Timber_{new}$	160	282	876	245	**1563**
Pumice	39	102	144	74	**359**
Total	**376**	**1161**	**2175**	**1034**	**4746**

Most buildings are founded on bedrock or stiff soil. At many building sites there is a thin organic soil layer at the top, typically 1-3 meters. It is a common procedure to excavate and remove this soil, refill, and put the foundations on 1-2 m thick manmade compact gravel pads. Therefore in very few cases only (less than 5%), the damage of buildings was related to soil failure under the foundations, mainly due to tilting, possibly caused by liquefaction or compaction due to the shaking. These cases are not included in the data sample. Almost all buildings in the South Iceland lowland are constructed in flat terrain (all the villages). Landslides did therefore not cause any damage, and effects due to topography on the ground shaking are also very limited and not considered. Ground shaking practically caused all damage.

3.5 Loss assessment

The loss assessment work started the day after the earthquake. The estimators worked in groups of two, one being the group leader. The assessment work procedure was as follows:

1. Property owner reports damage to his local insurance company, which informs the Iceland Catastrophe Insurance (ICI).
2. ICI estimators prepare the assessment work by familiarizing themselves with drawings and other related information about the damaged property.
3. ICI estimators perform first inspection of the property. All building damage is documented, marked on drawings and photos taken.
4. Estimators prepare a repair assessment report, if damage due to earthquake action is found. The assessment report includes a description of the damage and a cost estimate for the repairs. The repair cost estimate is the basis for compensation to the owner.

3.6 Damage database

A special database was designed to store all the damage data. It is related by Id-number for each building to the official real properties database (Registers Iceland). The estimated repair cost was divided into the following subcategories:

1. Excavation, fill and earthwork,
2. Foundations and bottom slab,
3. Exterior supporting structure (walls, columns, beams, stairways)
4. Roof structure
5. Interior supporting structure (walls, columns, beams, plates, stairways)
6. Interior finishing work (light party walls, mortar, suspended ceilings, ceiling cladding)
7. Interior fixtures, including kitchen and bathrooms, interior doors, flooring, wall tiles, etc.
8. Windows, glass, exterior doors, wall cladding etc.
9. Painting work outdoors and indoors including crack filling and surface treatment.
10. Plumbing (cold water, hot water and sewer pipes), radiators, electrical installations

The first five categories (1-5), cover structural damage, whilst the last five (6-10) cover the non-structural damage. Each of these 10 subcategories is split into sub-subcategories. In total the estimated damage for a given building can be split into 62 sub-subcategories.

4. DAMAGE STATISTIC

4.1 Damage

The complete damage database gives the possibility to map the main damage and weakness of the buildings. A number of houses suffered no damage, whilst others had small to severe damage, which in some cases was judged a total loss. In practice the epithet “total damage” was assigned to residential buildings that had repair cost of more than 50 to 70% of replacement value. Table 4.1 shows percentage of damaged buildings (including total loss) in each class and intensity level. The prevalence of damage is highest for pumice and old reinforced concrete buildings, and lowest for new timber buildings. The graphs in Fig. 4.1a show the proportion of undamaged, damaged, and totally damaged buildings for the five building classes as function of intensity level. As an example it can be seen from the figure, that for $\text{concrete}_{\text{old}}$ buildings at intensity level 3, around 20% of them suffer no damage, while 80% are “damaged”, and none suffer “total damage”.

The graphs in Fig. 4.1b show the mean loss for each intensity level, as well as showing how the damage is split between structural (subcategories 1-5) and non-structural damage (subcategories 6-10). Taking the $\text{concrete}_{\text{old}}$ buildings as example, the mean loss was found to be 5.3% for intensity level 3, and of these 15% are structural damage while 85% are non-structural damage. It should also be noticed that there is a significant step in mean damage ratio when going from intensity level 2 to 3, but less difference between level 3 and 4. Furthermore, the structural damage in terms of mean loss is small for all the building classes, even at intensity level 4. This is in harmony with the fact that no low-rise residential buildings collapsed in the 2008 Ölfus earthquake. Finally, Fig. 4.1b shows that the damage of new low-rise concrete and new low-rise timber houses is quite similar at all earthquake intensity levels. The average damage ratio for these building types is 3.0% and 3.9% at intensity level 4, respectively. For comparison the damage ratio for old concrete, and pumice buildings are 6.5% and 10.5% at intensity level 4, respectively. This means that expected damage ratio of new concrete building built after 1980 is less than 50% of expected damage ratio of old concrete building.

Most of the recorded damage is related to non-structural elements. For instance for new concrete and new timber houses, the non-structural damage is 91% and 81% of the total loss respectively at intensity level 4. For old timber, old concrete and pumice buildings it is 74.7%, 73.9% and 62.3% respectively at intensity level 4.

Table 4.1. Percentage of damaged buildings in each category in the Ölfus region, sorted after ground motion intensity level and building class.[1)]

Building class	Intensity level[1)] 1 0.05g – 0.09g	2 0.09g – 0.18g	3 0.18g – 0.34g	4 0.34g – 0.65g	Percentage
$Concrete_{old}$	2.8	22.0	79.1	80.6	**57.9**
$Concrete_{new}$	3.9	10.3	59.9	74.2	**52.3**
$Timber_{old}$	8.9	24.4	71.0	57.6	**46.8**
$Timber_{new}$	13.8	14.9	51.0	61.2	**42.3**
Pumice	7.7	38.2	79.9	70.2	**58.2**
Total	**8.8**	**20.6**	**64.2**	**69.1**	**50.2**

1) The data is from 2010 and at that time some (very few) of the claims had not been settled.

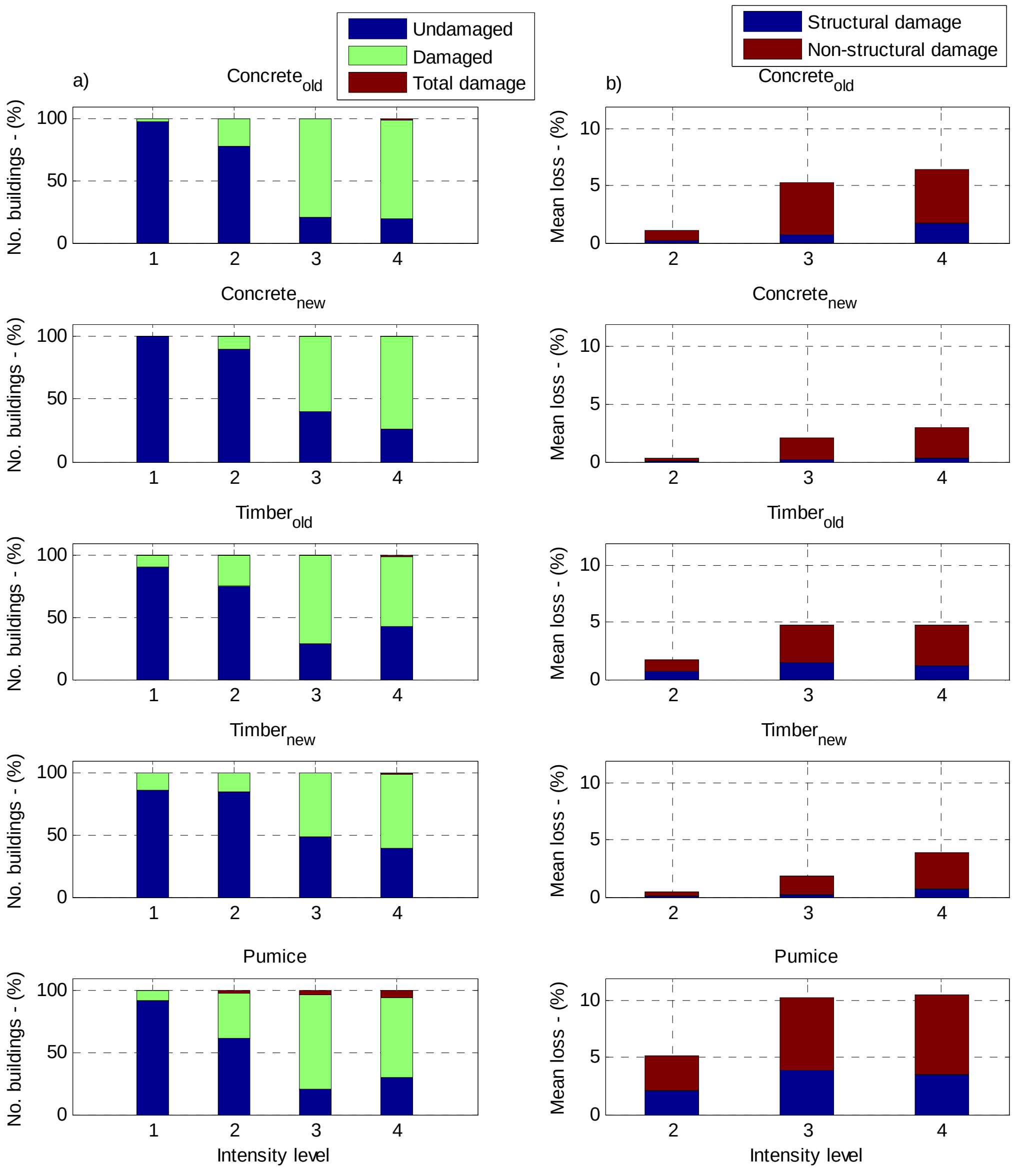

Figure 4.1. Damage data. a) Number of buildings, undamaged, damaged, and totally damaged as function of intensity level for the five building classes. b) Damage ratio as function of intensity level for the five building classes, and how it is split into structural and non-structural damage.

4.2 Sub classification of structural and non-structural damage

In Fig. 4.2 the damage is classified into ten subcategories as defined in chapter 3.6. Fig.4.2a shows the damage for intensity levels 1 and 2 combined, and Fig. 4.2b for intensity levels 3 and 4 combined. From the figure it can be seen that for all building classes and both the combined intensity levels (i.e. 1&2 and 3&4), columns 7 and 9 are significantly higher than the others. This means that the highest monetary damage was due to interior fixtures, flooring, tiles etc., and cosmetic surface damage that requested paint-work. For instance, for $concrete_{new}$ buildings at all four intensity levels (i.e. 1, 2, 3, and 4) the two damage types contributed to 80% of the total damage. Similarly, 73% for the $timber_{new}$ buildings, 63% for $concrete_{old,}$ 53% for $timber_{old}$, and 37% for pumice buildings. Figure 4.2a also shows that structural damage of $concrete_{new}$ and $timber_{new}$ buildings is only found within type 2 and 5 damage classes at intensity levels 1 and 2 combined. Since most of the damage is in subcategories 7 and 9, it is interesting to see how this damage can be split up. Focusing only on new concrete and new timber buildings and taking all the four intensity levels together, the results are shown in Fig. 4.3 and Fig. 4.4. The figures show that damage of flooring (>66% of subcategory 7) and indoor paint-work (>84% of subcategory 9) dominate the repair costs for $concrete_{new}$ and $timber_{new}$ buildings.

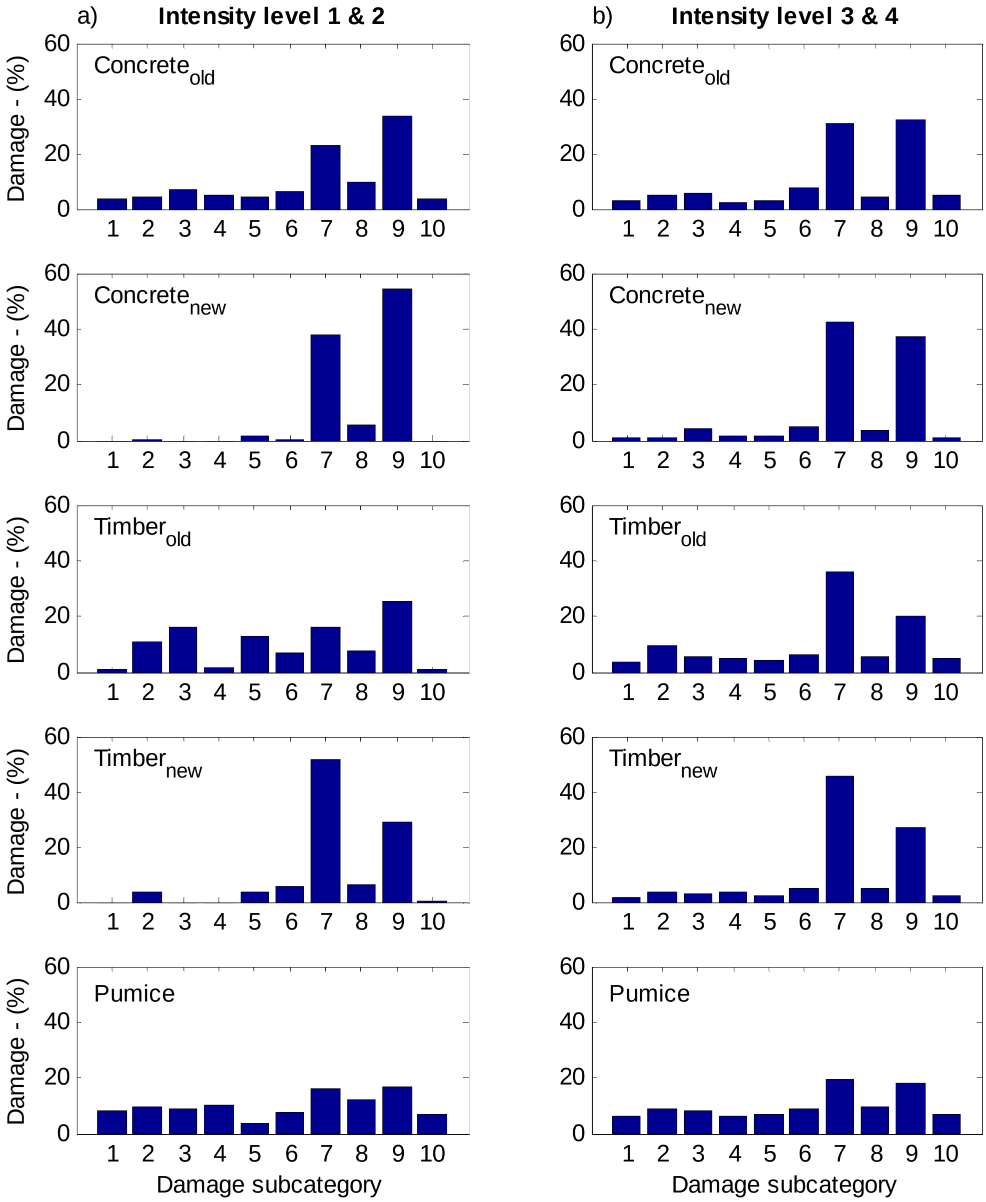

Figure 4.2. Classification of damage in ten subcategories (see chapter 3.6) for the five building classes. a) At intensity level 1 and 2 combined, and b) at intensity level 3 and 4 combined

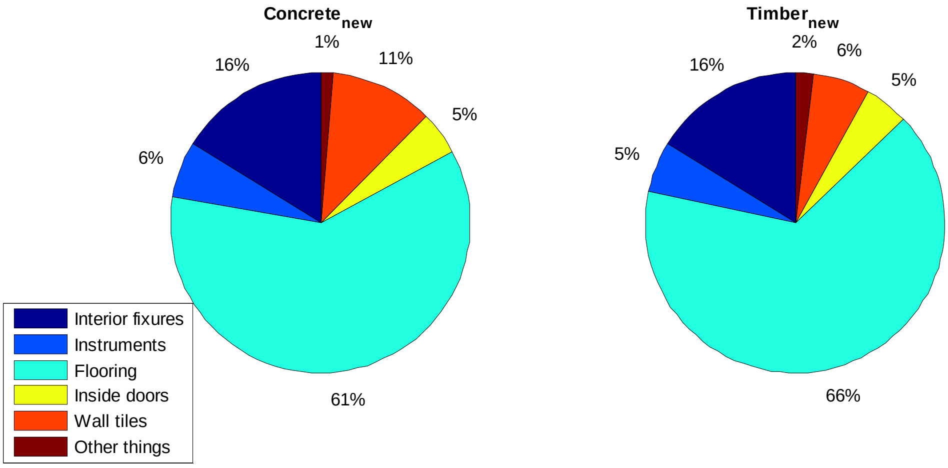

Figure 4.3. Split up of subcategory 7 (see section 3.6) for concrete$_{new}$ and timber$_{new}$ buildings.

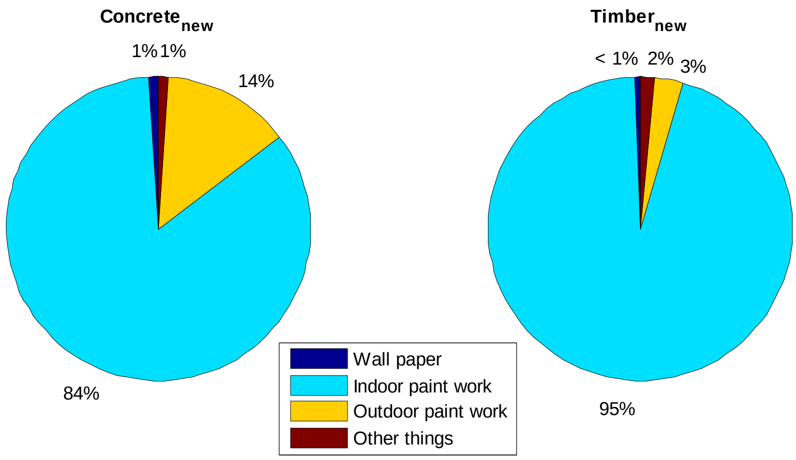

Figure 4.4. Split up of subcategory 9 (see section 3.6) for concrete$_{new}$ and timber$_{new}$ buildings.

5. SUMMARY AND CONCLUSIONS

A shallow 6.3 (M_w) magnitude earthquake struck the Ölfus region in South Iceland 29th of May 2008. This is the largest agricultural region in Iceland. A detailed and comprehensive property database exists for the area as well as for the whole country. Catastrophe insurance of all buildings is mandatory, and therefore the damage was systematically estimated for all affected buildings. In order to carry out damage and vulnerability analysis, all damage data was classified in subcategories stored in an electronic database.

The majority of residential buildings in the affected area are low-rise, built of concrete, timber or pumice materials. In this study the focus was on these building types. The data sample consists of 4,746 buildings, classified in five construction classes; two categories of reinforced concrete shear-wall buildings built before and after 1980, two categories of timber buildings built before and after 1980, and finally one category of pumice buildings. Damage of every building was investigated and reported by trained assessors and the repair cost estimated. The damage was divided into 10 subcategories and each subcategory is divided into 4 to 8 items. In total, the damage is classified into 62 sub-subcategories. About 50% of all buildings in the area suffered damage. This loss was covered by the Icelandic Catastrophe Insurance. Only 0.44% were judged totally damaged. None of these collapsed or caused injuries or deaths, but the damage was so severe that repair was impractical.

Four ground motion intensity levels were used to relate observed damage to the earthquake action at each site. Since low-rise buildings are stiff with a short natural period, it was preferred to use a PGA parameter to define the intensity level, based on an earthquake wave attenuation model for Iceland. This model predicts the median value of both horizontal acceleration components.

The damage analysis shows that damage of new low-rise concrete and new low-rise timber houses is quite similar. Expected damage of old concrete and pumice buildings is significantly higher at all intensity level than the for new concrete and new timber buildings.

The damage of structural load-bearing systems was limited for all building classes. The strength of the structural system seem to be sufficient to protect human lives for magnitudes of order 6 to 6.5. Non-structural damage dominate the monetary damage for all building classes and at all intensity levels. Here, it is mainly damage in flooring, and cosmetic surface damage that paint work. In modern earthquake resistance design, the main focus is on the structural load-bearing system and its strength to withstand earthquakes. Nevertheless no special earthquake resistance design is generally made to limit damage in the two before mentioned subcategories, which contribute to most of the damage.

The building stock in Iceland is quite uniform, and the damage distribution between subcategories observed in the Ölfus region are expected to be similar in other regions in the country, i.e. for similar earthquake magnitudes. The results may also be of value in considering potential losses from seismic ground shaking for similar buildings in other countries. However building traditions vary considerably between countries.

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