Reassessment of intensity estimates from vulnerability and damage distributions: the 2011 Lorca earthquake

S. Martínez-Cuevas & J. M. Gaspar-Escribano

This is a post-peer-review, pre-copyedit version of an article published in Bulletin of Earthquake Engineering. The final authenticated version is available online at: http://dx.doi.org/10.1007/s10518-016-9913-8

Reassessment of Intensity Estimates from Vulnerability and Damage Distributions: the 2011 Lorca Earthquake.

S. Martínez-Cuevas[1] and J.M. Gaspar-Escribano[1]

(1) ETSI Topografía, Geodesia y Cartografía, Universidad Politécnica de Madrid, Spain
e-mail: sandra.mcuevas@upm.es; jorge.gaspar@upm.es phone: +34 913366441

Abstract

This paper presents a reassessment of the seismic intensity estimated for the 2011 Lorca (southeastern Spain) earthquake based on detailed vulnerability data and its comparison with the observed damage. Building and urban data are gathered in selected areas during a field campaign and are completed with office work. The significance of vulnerability modifiers in the final vulnerability distribution is analyzed, and their relation with observed damage trends is explored. A direct application of the vulnerability modifiers is not capable of reproducing the observed damage patterns. A significant increase of vulnerability related to the performance of buildings presenting soft story is required to reach a damage distribution consistent with intensity estimates in the study areas. Accordingly, an intensity increase in certain study zones (as compared to other areas of the city of Lorca) is suggested. Although the approach followed in this study is applied in a city of Spain, it can be extrapolated to other areas where detailed vulnerability assessment is feasible and damage data are available.

Key words: intensity, vulnerability, damage, behavior modifier, Lorca.

1. Introduction

Macroseismic intensity represents the impact of earthquake ground motions comprising the effects on humans and on built and natural environments. It is a discrete (not continuous) quantity that averages multiple and diverse input data, such as reported damage, human reaction and ground failure. This approach is really interesting because it integrates a rich and miscellaneous amount of information in a single parameter representative for a certain administrative or geographical unit. But at the same time, part of the information is averaged out and leads to a loss of resolution. For relatively large areas, especially if geographical variations on damage or loss estimates are perceived, this approach should be refined by reassessing intensity estimates in smaller geographical units.

In ex-ante seismic risk analysis, the estimation of expected damage (or loss) distribution demands establishing a priori an earthquake ground motion scenario (that may include source and site effects) and the vulnerability distribution. Conversely, details of the damage (loss) distribution are analyzed in order to identify possible damage-controlling patterns in ex-post evaluations. Specifically, the distribution of vulnerability may be reassessed and combined with the observed damage trends in order to investigate the performance of different building elements or configurations. This finer evaluation of vulnerability distribution could alter preconceived ideas about the actual cause of damage distribution and vary the initial intensity estimate. The present paper explores this idea using as study case the 2011 Lorca earthquake.

The 2011 Lorca earthquake is the most significant event in the last decades in Spain for several reasons; it caused nine fatalities; it produced notable damage not only to traditional but also to modern buildings; it led to economic losses of about 1000M € (only the toll covered by the Spanish insurance consortium reaches 500 M€; CCS, 2014); and it made thousands of people to be displaced and reallocated in temporary tents and households. Additionally, it occurred in a relatively well-studied seismically active area, with relatively high hazard, where earthquake-resistant provisions are enforced (NCSE-02, 2002).

The sequence started on 2011 May 11thand lasted less than two months. The main event had a Mw magnitude of 5.2 and it was preceded by a Mw 4.6 foreshock (e.g., Morales et al., 2014 and references therein). Recorded ground motions show a short duration of the strongest phase (below 2 seconds) and PGA values of 0.36 g in a single horizontal component (Cabañas et al. 2014).

An EMS intensity degree of VII was assigned to the main-shock in Lorca city (IGN, 2011). The shallowness and proximity of the earthquake source to the urban area and the effects of rupture directivity and soil amplification are invoked to explain the relatively large ground motions observed (López-Comino et al. 2014; Santoyo 2014, Navarro et al. 2014; Alguacil et al. 2014).

Additionally, the poor performance of buildings exhibiting soft stories, short and trapped columns and the parapets was patent. The incidence of damage was not openly higher in older, non-engineered buildings than in modern constructions. A main cause indirect damage was related to the fall of broken pieces of non-structural and ornamental elements (parts of infill walls, ledges, barriers, parapets) to the streets. These modes of earthquake damage are not adequately considered in seismic risk models. Thus, urban risk models aiming at reproducing the 2011 scenario are not capable of predicting the damage distribution at a detailed scale (Rivas-Medina et al. 2014). Overall, the aftermath of the 2011 Lorca earthquake is considered too harmful for the relatively small magnitude of the event and the expected performance of code-compliant constructions (Benito et al., 2012).

In this paper, a reevaluation of the intensity in the city of Lorca after the 2011 May 11th earthquake is presented. An analysis of seismic vulnerability of selected districts of Lorca, taken as representative of different types of constructions, urban configurations and recording observed damage after the 2011 Lorca event, is conducted. An exploratory study is carried out with the goal of understanding and quantifying whether the urban arrangement and local constructive practice have a marginal influence on seismic vulnerability or may lead to significant variations on vulnerability distributions. After crossing these data with the observed damage distribution, a more detailed reassessment of the macroseismic intensity estimates is attempted.

2. Theoretical background

The recognition of building typologies during several on-site campaigns and the availability of actual damage data for the 2011 Lorca earthquake conforms significant amount of data and observations that makes the empirical definitions of intensity and damage suitable for this work. The main features of empirical methods for intensity assessment, including vulnerability and damage descriptions, are provided in this section.

Macroseismic intensity scales are structured in intensity degrees that account for qualitative and quantitative differences of the incidence of an earthquake over human beings and the natural and built environment. Damage grades are used to describe this incidence on buildings, and depend principally on ground motion severity and building vulnerability.

The European Macroseismic Scale (Grünthal, 1998) considers twelve intensity degrees running from *I-Not felt* to *XII-Completely devastating*, defined in terms of relative estimates (qualified as *few*, *many* and *most*) of the distribution of damage grades on buildings of different vulnerability class. The EMS98 defines five damage grades (from negligible or slight to destruction) degrees described by damage to structural and non-structural elements of masonry and of reinforced concrete (RC) buildings. Six vulnerability classes are defined, from A (more vulnerable) to F (less vulnerable), including a qualitative description of the type of structure (masonry, RC, steel and wood) and the *most likely* related vulnerability class, as well as a range of *probable* and *exceptional* related vulnerability classes. Vulnerability modifiers or factors such as building quality, state of preservation, building regularity, relative position in the urban setting and the level of seismic design are taken into account to eventually shift a building from the most likely vulnerability class to a probable or exceptional class.

As intensity scales use vulnerability classifications based on structural typology primarily, the definition of different damage grades must be expressed in terms of damage impact on structural components, ranging from no damage to virtually total collapse of the building. Given that the lower damage grades do not involve the structure, a complementary description of the impact on non-structural elements is also provided.

One of the characteristics of the EMS98 scale is that is expressed in qualitative terms or in quantitative ranges offering a wide range of possibilities. This approach simplifies and facilitates field campaign assessments and cross-comparison of the aftermath of different damaging earthquakes. However, for other applications requiring higher degree of detail, such as urban risk assessment based on the performance of individual buildings (not a set of buildings taken collectively), the use of a continuous vulnerability / damage scale would be more appealing.

This is surpassed by the vulnerability index approach (e. g., Benedetti and Petrini 1984), which describes building vulnerability, including the effects of different vulnerability modifiers, through quantitative estimates. An update of both approaches in an integrated scheme is accomplished in the Risk UE project (Milutinovic and Trendafiloski, 2003; see below for details). The integration of definitions of vulnerability classes and damage degrees and the harmonization of approaches to intensity estimates is an evolving issue of actual interest, as evidenced in initiatives such as the World Housing Encyclopedia and PAGER project, the Global Earthquake Model Earthquake initiative and the International Macroseismic Scale (Porter et al. 2008, 2012; Spence and Foulser-Piggott, 2014).

In this context, the Risk UE approach incorporates membership functions in order to translate the EMS98 definitions of quantities (*a few*, *many*, *most*) into quantitative, numeric estimates of the vulnerability index. Additionally, it defines procedures to express the discrete damage probability matrices into continuous damage probability distributions (Milutinovic and Trendafiloski, 2003).

3. Data and Methods

3.1. Vulnerability assessment of exposed buildings

The dwelling building stock of the city of Lorca is composed by 15.000 buildings. This amount is large and a building-by-building assessment would be extremely time- and resource-consuming. Two options may be considered: making a detailed –scale study in selected representative city areas of small size that could be extrapolated to the entire city; or carrying out a city-scale assessment with lower degree of detail and more poorly constrained statistical extrapolations. The first option is followed in this study.

A procedure to select and characterize the seismic vulnerability of representative areas of Lorca is set up. It consists of several phases (Figure 1). The three first deal with the selection of target zones and the compilation of data collection from the available resources. The fourth phase includes a field campaign aimed at completing and validating the preliminary results of the previous phases. The vulnerability assessment method, inputs and results are described in phases 5, 6 and 7, respectively.

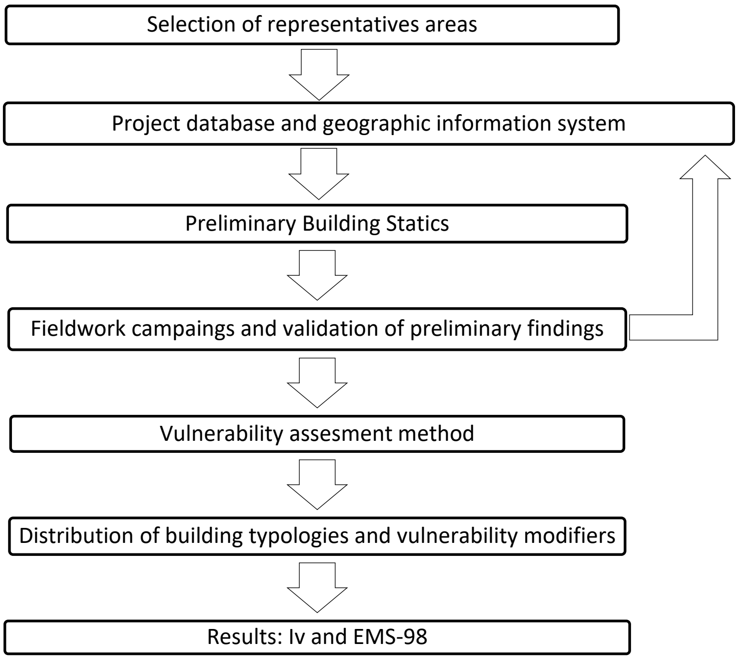


Figure 1. Diagram showing the procedure to estimate the seismic vulnerability in this study

3.1.1. Selection of representative areas.

An initial analysis of urban sectors of Lorca and the distributions of exposed buildings representative of several epochs and constructive techniques, with singular urban and constructive features (including urban planning), age of urban development and building typologies) is carried out. Additionally, the targeted areas should contain a sufficient amount of buildings to provide reliable inferences for the rest of the city and a significant damage data as a result of the 2011 earthquake.

Two main types of urban areas are observed. One is the historic center, with irregular arrangement of narrow streets and predominance of old, masonry buildings. The other one is an urban development of the second half of the XX century, with regular, wider street networks and prevalence of RC frame structures.

Three neighborhoods located in the northern part of Lorca are selected to carry out the present study (Figure 2): Barrio de San Diego, Barrio de Santiago and Barrios Altos. Barrios Altos represents the oldest part if the city, with relatively old, short buildings lacking earthquake-resistant design. Barrio de Santiago and Barrio de San Diego develop during the expansion of the city from the middle XX century up to date and contain buildings constructed under the frame of different seismic codes. They differ in the urban characteristics, such as the presence of isolated buildings or of tall buildings, more notable in Barrio de San Diego. Summing up, a significant sample of 467 buildings is assessed in this work, analyzing each building one-by-one and directly observing the characteristics of each constructive unit.

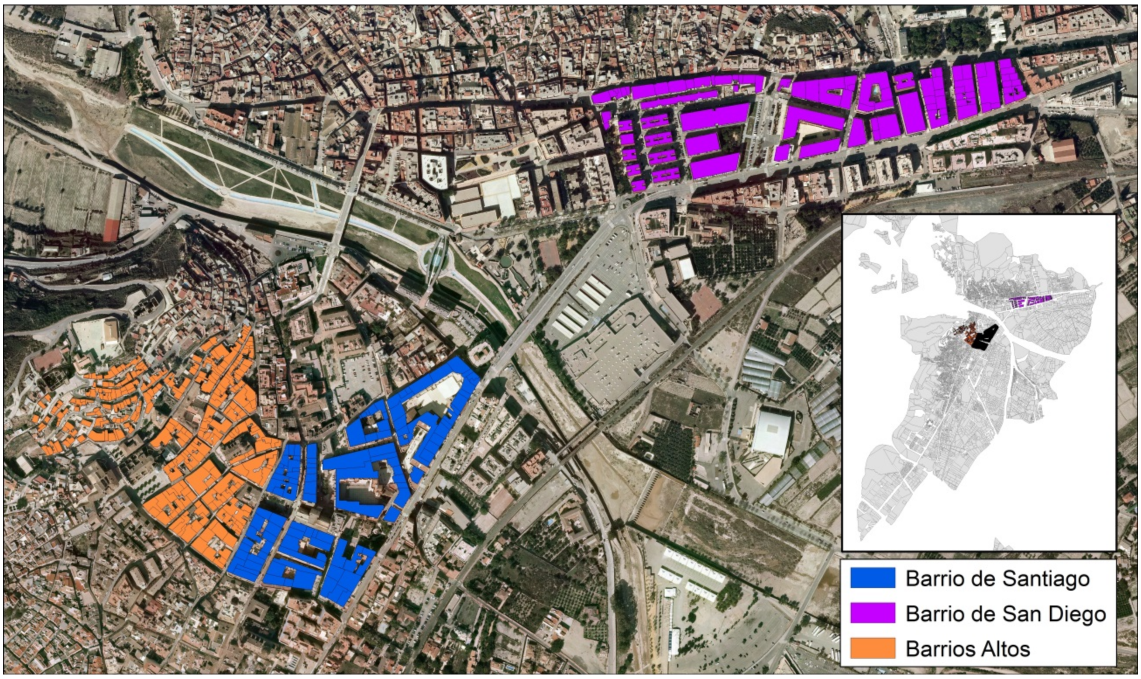


Figure 2. Location of the study in Lorca.

3.1.2. Development of project database and geographic information system

A buildings database and a geographic information system (GIS) are developed for the project. The source data are obtained from the Spanish Cadaster website. The basic geographical unit is the cadastral construction. Tables with different classes of information and files (in shapefile format) containing georeferenced polygons that represent the limits of cadastral constructions are provided.

As a single building unit may be composed by several cadastral constructions (corresponding to attics, terraces, inner courtyard among others), a thorough edition process was carried out for depurating the source data and bearing a single polygon for each building (corresponding to the perimeter).

The combined representation of satellite images and the cadaster shapefiles in the GIS facilitated the delimitation of these polygons. Figure 3 illustrates the effect of this data depuration by removing the cadastral parcels of no interest for the purpose of this work.

Additionally, all attributes of the Cadaster database tables were examined and only the attributes relevant for the study were retained. These include, besides the cadastral reference, the geometry, the full address, the number of stories and the year of construction. In this way, each record of the database represents one building unit and integrates in the different fields all the data originally dispersed in different tables. New fields, such as the *building height*, the *level of code earthquake-resistant design* and *the building typology* are added in subsequent stages of the work.

The outcome of this process leads to a drastic reduction of the number of records (from 1987 to 467) managed in the project.

Figure 3. Example of depuration of original cadastral parcels (left) to obtain the building polygons relevant for the study (right).

3.1.3. Building distributions in both areas.

Figure 4 shows the distribution of buildings per construction age and number of stories. These periods correspond to significant changes on constructive techniques and the emergence of new building typologies in Lorca.

Barrios Altos is the oldest of the three areas of study, as most buildings were constructed before 1960. It is composed by 272 buildings (including 7 buildings in ruined conditions prior to the earthquake), mainly single-family homes, detached houses typically with 1-3 stories and wall masonry structure. No high buildings (6 or more stories) are found in this area.

Barrio de Santiago contains 104 buildings, most of them for collective use, with higher number of stories (peaking in 5 stories and including high buildings with more than 6 stories) and different structural types (reinforced concrete and masonry). Most of them (about 80%) were built after 1960, coinciding with the development of reinforced concrete constructions.

Barrio de San Diego is also a relatively modern area with 91 buildings. The predominant building type presents a reinforced concrete structural system, with three or more stories, and is arranged and constitutes relatively large blocks which plan form differ from one building to another. They are dedicated for multifamily residential use.

Barrio de Santiago and *Barrio de San Diego* present similar distributions of building elevations and date of construction. However, they are treated individually in this study because they are separated geographically and they present different urban features. The urban layout in *Barrio de Santiago* is more organic: the streets are narrower, older and recent buildings coexist in the same block, producing noticeable height differences between them. By contrast, the urban layout in Barrio de San Diego is reticulated, with wide streets and buildings of more uniform elevation and larger parcels. Large, closed building blocks with central collective space are characteristic of this area.

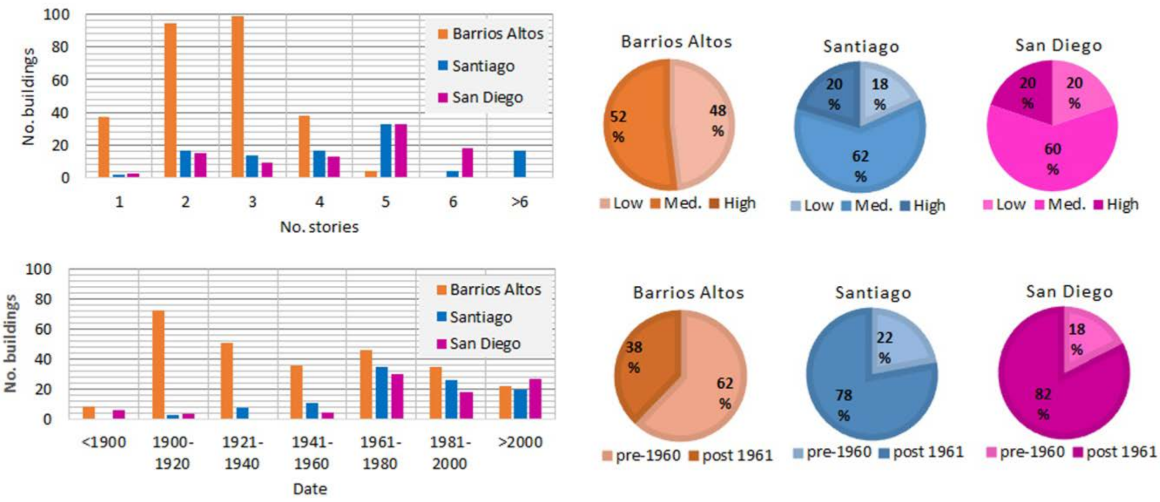


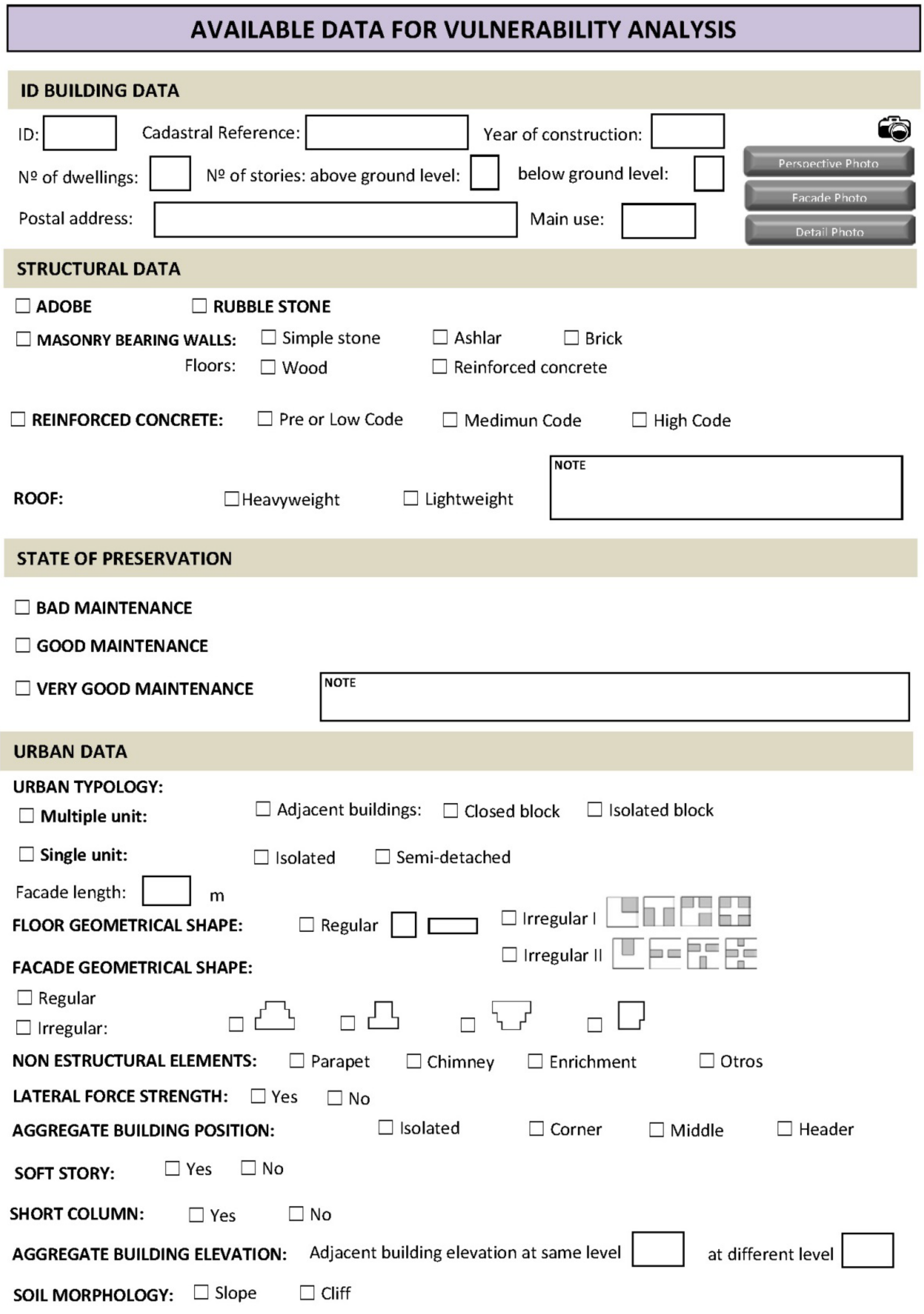
Figure 4. Building distributions in height (or number of stories) (top) and construction date (bottom). High, medium (Med.) and high buildings respectively have 1-2, 3-5 and 6 or more stories.

3.1.4. Fieldwork campaigns for data collection and validation of preliminary conclusions.

Two walk-down campaigns were carried out to collect data required to confirm preliminary conclusions regarding the distribution of construction elements that determine non-structural building components of other vulnerability modifiers.

A template is designed to help data collection (Figure 5). It contains a comprehensive amount of fields that can be used in future seismic vulnerability and seismic risk studies. It is divided in four blocks. The first block contains general building data that does not require any expertise, such as address, building year and number of dwellings. The second block includes constructive features of the building structure. The third block refers to the state of conservation. Finally, the fourth block to addresses urban characteristics (constructive typologies) and all possible urban configurations that may affect the seismic performance, such as plan and vertical irregularities.

For each building contained in the database, a specific form is completed. This form includes the contour shape of the building and different fields to introduce/modify data regarding structural and non-structural parameters. Examples of common changes that had to be made in the building database after the conclusion of field campaign are the separation of buildings that share the same cadastral unit but that actually are different buildings, building with a land use that is not exclusively residential (usually commercial and residential) and differences in building height.



AVAILABLE DATA FOR VULNERABILITY ANALYSIS

ID BUILDING DATA

ID: ☐ Cadastral Reference: ☐ Year of construction: ☐
Nº of dwellings: ☐ Nº of stories: above ground level: ☐ below ground level: ☐
Postal address: ☐ Main use: ☐

STRUCTURAL DATA

☐ **ADOBE** ☐ **RUBBLE STONE**
☐ **MASONRY BEARING WALLS:** ☐ Simple stone ☐ Ashlar ☐ Brick
Floors: ☐ Wood ☐ Reinforced concrete
☐ **REINFORCED CONCRETE:** ☐ Pre or Low Code ☐ Medimun Code ☐ High Code
ROOF: ☐Heavyweight ☐ Lightweight
NOTE

STATE OF PRESERVATION

☐ **BAD MAINTENANCE**
☐ **GOOD MAINTENANCE**
☐ **VERY GOOD MAINTENANCE**
NOTE

URBAN DATA

URBAN TYPOLOGY:
☐ **Multiple unit:** ☐ Adjacent buildings: ☐ Closed block ☐ Isolated block
☐ **Single unit:** ☐ Isolated ☐ Semi-detached
Facade length: ☐ m
FLOOR GEOMETRICAL SHAPE: ☐ Regular ☐ Irregular I ☐ Irregular II
FACADE GEOMETRICAL SHAPE:
☐ Regular
☐ Irregular: ☐ ☐ ☐ ☐
NON ESTRUCTURAL ELEMENTS: ☐ Parapet ☐ Chimney ☐ Enrichment ☐ Otros
LATERAL FORCE STRENGTH: ☐ Yes ☐ No
AGGREGATE BUILDING POSITION: ☐ Isolated ☐ Corner ☐ Middle ☐ Header
SOFT STORY: ☐ Yes ☐ No
SHORT COLUMN: ☐ Yes ☐ No
AGGREGATE BUILDING ELEVATION: Adjacent building elevation at same level ☐ at different level ☐
SOIL MORPHOLOGY: ☐ Slope ☐ Cliff

Figure 5. Template used in the field campaign to collect input data for the seismic vulnerability analysis.

3.1.5. Vulnerability assessment method.

The initial vulnerability assessment approach followed in this study is the vulnerability index method, considering structural and non-structural building components, as proposed by Milutinovic and Trendafiloski (2003). For clarification and to aid the interpretation of results, the EMS98 vulnerability approach is also used.

Five main building typologies are found in Lorca, one of reinforced concrete structure and five masonry structure typologies (Table 1).

Table 1. Main building typologies found in the study areas

TYPOLOGY		DESCRIPTION
Masonry walls	**M1.1**	Unreinforced masonry bearing walls of rubble stone and fielstone
	M1.2	Unreinforced masonry bearing walls of simple stone
	M1.3	Unreinforced masonry bearing walls of massive stone
	M3.1	Unreinforced masonry bearing walls with wooden slabs
	M3.4	Reinforced concrete slabs
Reinforced Concrete	**RC1**	Concrete frames with regular unreinforced masonry infill walls

For each typology, a vulnerability index (I_V) value ranging from roughly 0 (least vulnerable) to roughly 1 (most vulnerable) is assigned. This index is not a fixed number and it is defined by a most likely value I_V* together with an interval of plausible values (I_V^-, I_V^+) and interval of possible values ($I_V^{\min}$, I_V^{max}). Figure 6 illustrates the variability that may reach the vulnerability index specifically for the building typologies observed in Lorca. The I_V^{max} value may increase as much as 0.5 units in some M1.1 buildings and may decrease up to -0.02 for some RC1 typologies, according to the original values provided by Milutinovic and Trendafiloski (2003).

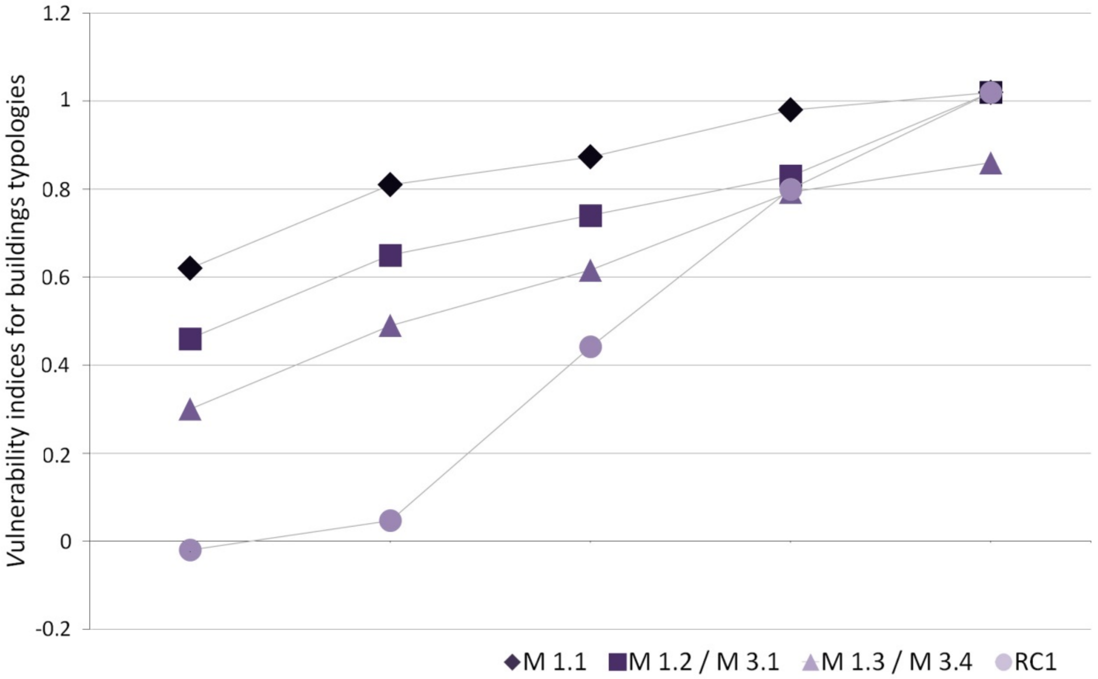


Figure 6. Range of I_v values for the building typologies identified in the study areas.

The vulnerability index I_V* of a particular building must be modified taking into account its specific features. One is the level of earthquake-resistant design, directly related to the enforcement and compliance of seismic codes, which is accounted for through a region-dependent modifier $\Delta M_{R.}$. For a given city, all buildings constructed in the same year and belonging to the same vulnerability class present the same value for ΔM_R. Other factors modifying building vulnerability are associated to geometrical features of the building (number of stories, irregularities in vertical planes, plan irregularities, roof loads, length of façade), the state of conservation and to its position in relation to the adjacent buildings, if exists (height in relation to adjacent buildings, position on elevation, terrain morphology and position of the building in the block).

They are collectively represented by the behavior modifier ΔM_C. Thus, the characteristic vulnerability index of a particular building Iv is obtained by adding the modifiers to its most likely vulnerability index $Iv*$:

$$Iv = Iv^* + \Delta M_R + \Delta M_C$$

In this work, modifier ΔM_R is quantified taking into account the year of construction of each building, which marks the level of code-compliant seismic design. Figure 7 shows the values of the regional modifier in Lorca as a function of time, noting the changes introduced by the application of the respective seismic codes in force. The actual values are adopted from the analysis of damaged buildings after the Lorca 2011 earthquake by Feriche el al. (2012).

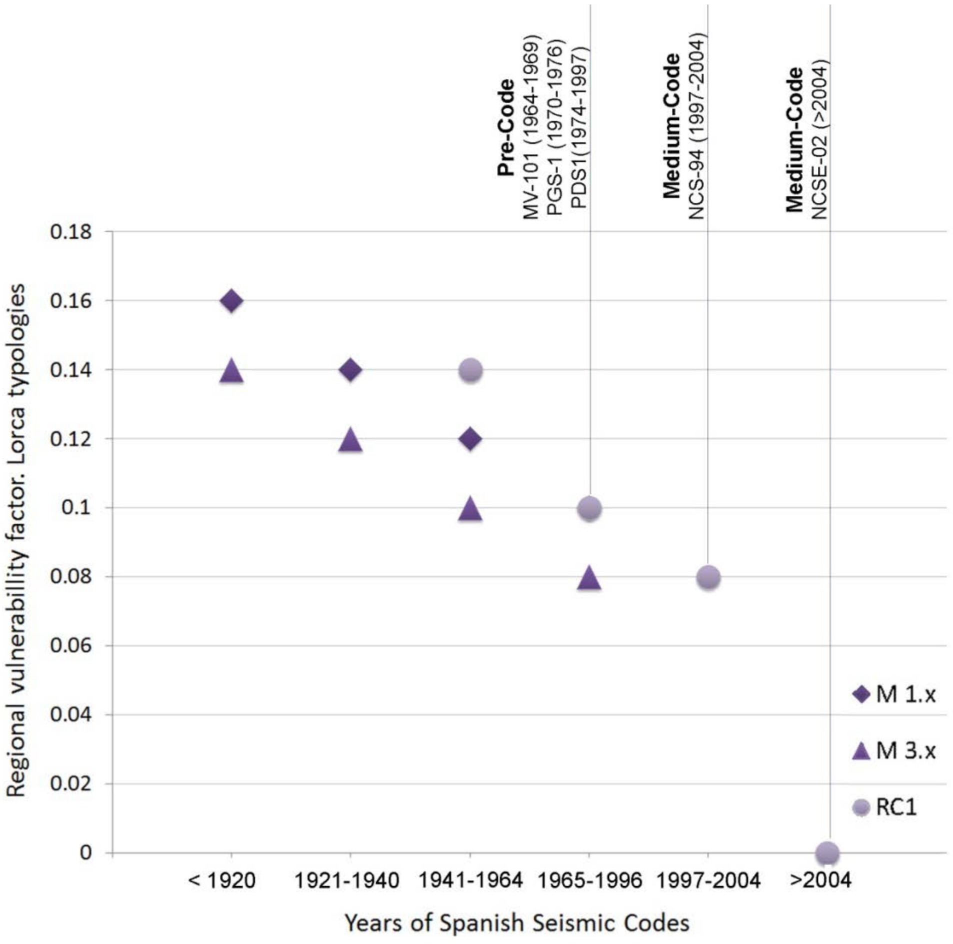


Figure 7. Regional vulnerability modifier (ΔM_R) values for Lorca as a function of time. Time intervals are defined considering the changes of the successive Spanish Seismic Code in Lorca.

Regarding the behavior modifier ΔM_C, this work follows the approach of Milutinovic and Trendafiloski (2003), expect those related with plan irregularity, height in relation with adjacent buildings and façade length, which are taken from Lantada et al. (2010). Table 2 contains a description of the behavior modifiers used in this study for masonry and reinforced concrete typologies. They are divided in nine categories. The total behavior modifier for a single building is the sum of the individual values for these nine categories. The actual values for the present work are shown in Figure 8. For example, buildings with a good state of conservation and bounded by taller buildings present low ΔM_C values, whilst buildings located at the header of the block and with more than 8 stories have higher ΔM_C values.

Table 2. Behavior modifiers used in this study (based on Milutinovic and Trendafiloski, 2003; and Lantada et al., 2010).

MASONRY BUILDINGS	**REINFORCED CONCRETE BUILDINGS**
1. STATE OF PRESERVATION *1.1 Very Good maintenance (< 10 years); 1.2 Good maintenance; 1.3 Bad maintenance (> 40 years)*	1. STATE OF PRESERVATION *1.1 Very Good maintenance (< 10 years); 1.2 Good maintenance; 1.3 Bad maintenance (> 40 years)*
2. PLAN IRREGULARITY *2.1 Regular; 2.2 Irregular*	2. PLAN IRREGULARITY *2.1 Regular; 2.2 Irregular*
3. VERTICAL IRREGULARITY *3.1 Regular; 3.2 Irregular, 3.3 Soft-story*	3. VERTICAL IRREGULARITY *3.1 Regular; 3.2 Irregular, 3.3 Soft-story*
4. ROOF *4.1 Light; 4.2 Heavy*	4. ROOF *4.1 Light; 4.2 Heavy*
5. SOIL MORPHOLOGY *5.1 Flat; 5.2 Slope*	5. SOIL MORPHOLOGY *5.1 Flat; 5.2 Slope*
6. AGGREGATE BUILDING POSITION *6.1 Isolated, 6.2 Middle; 6.3 Corner; 6.4 Header*	6. AGGREGATE BUILDING POSITION *6.1 Isolated, 6.2 Middle; 6.3 Corner; 6.4 Header*
7. AGGREGATE BUILDING ELEVATION 7.1 Adjacent buildings at same level; 7.2 Adjacent buildings higher; 7.3 An adjacent building higher and the other at the same level; 7.4 An adjacent building lower and the other at the same level ; 7.5 Adjacent building lower; 7.6 An adjacent building lower and the other higher	7. AGGREGATE BUILDING ELEVATION 7.1 Adjacent buildings at same level; 7.2 Adjacent buildings higher; 7.3 An adjacent building higher and the other at the same level; 7.4 An adjacent building lower and the other at the same level ; 7.5 Adjacent building lower; 7.6 An adjacent building lower and the other higher
8. FACADE LENGHT *8.1 L≤15m; 8.2 L>15m*	
9. NUMBER OF FLOORS 9.1 Low (1 or2); 9.2 Medium (3, 4 or 5); 9.3 High (≥6)	9. NUMBER OF FLOORS 9.1 Low (1or3); 9.2 Medium (4,5,6or7); 9.3 High (≥8)

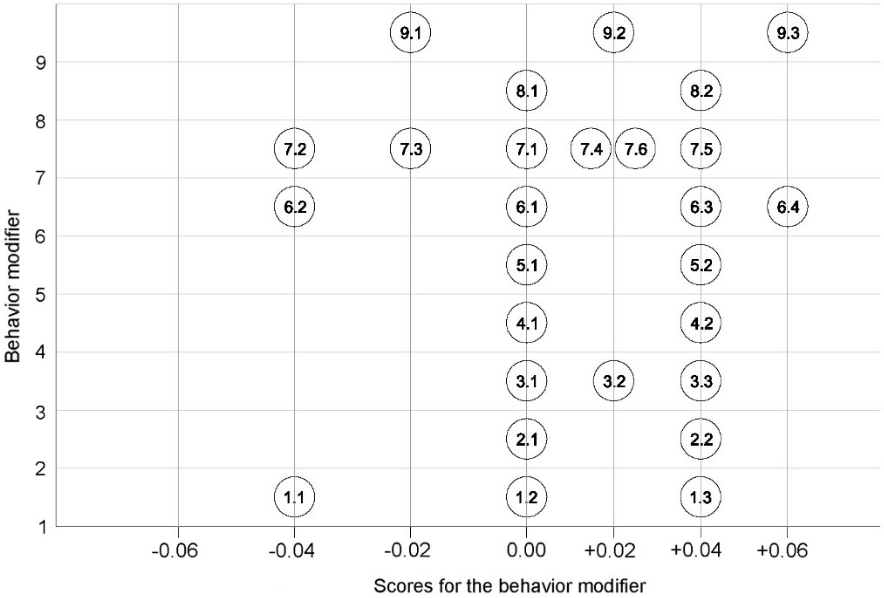


Figure 8. Values of the behavior modifier based on Milutinovic and Trendafiloski (2003) and Lantada et al. (2010).

3.1.6. *Analysis of geographical distribution of building typologies and modifiers.*

The distribution of building typologies in the study areas, resulting from the preliminary analysis and confirmed with the data gathered in the field survey, is shown in Figure 9. It is confirmed that reinforced concrete buildings (RC1 typology) predominate in *Barrio de Santiago* and *Barrio de San Diego*. Very few, dispersed masonry buildings that are apart from the urban planning are found in *Barrio de San Diego*. *Barrio de Santiago* presents more variety of building typologies, with a significant presence of some masonry typologies (as M3.4). *Barrios Altos* is mainly composed by different masonry typologies, including the oldest buildings with unreinforced masonry bearing walls of rubble stone and fieldstone (typologies M1.1) and the more modern ones with unreinforced masonry bearing walls with wooden slabs or reinforced concrete slabs (M3.1 y 3.4).

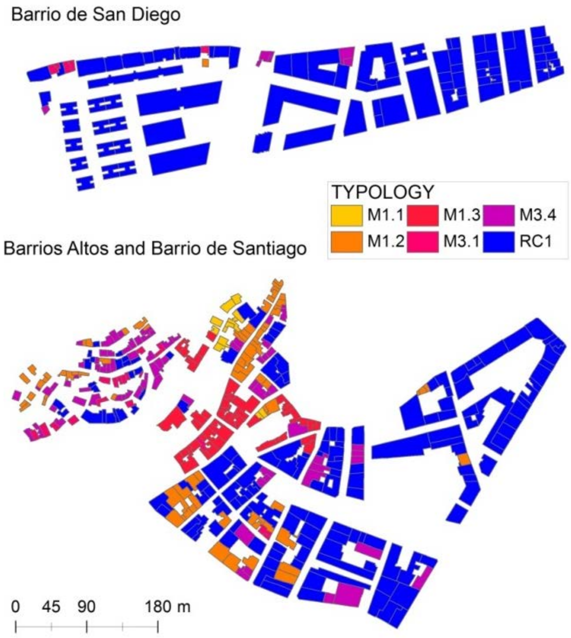


Figure 9. Distribution of building typologies in the study areas of Lorca.

Figure 10 shows the geographical distribution of significant vulnerability modifiers in the three study areas, including plan and vertical irregularities and aggregate building position and elevation.

All areas present irregular configuration, more markedly in Barrios Altos, though. Vertical irregularities, as (open and closed) cantilevers, setback components, etcetera, occur commonly, as elder and present urban normative do not ban them and it is a habitual technique in building execution (Figure 10 a). It is remarkable the abundance of constructions with soft story in *Barrio de San Diego* and *Barrio de Santiago*. Plan irregularities are observed all around *Barrios Altos*, which is characterized by an organic urban structure (i. e., an unregulated, natural expansion) controlled by the changing topography around the castle hill. *Barrio de Santiago* in and *Barrio de San Diego* present a reticular urban structure, reflected by the orthogonal subdivision of building parcels that collectively form a regular plan configuration (Figure 10 b).

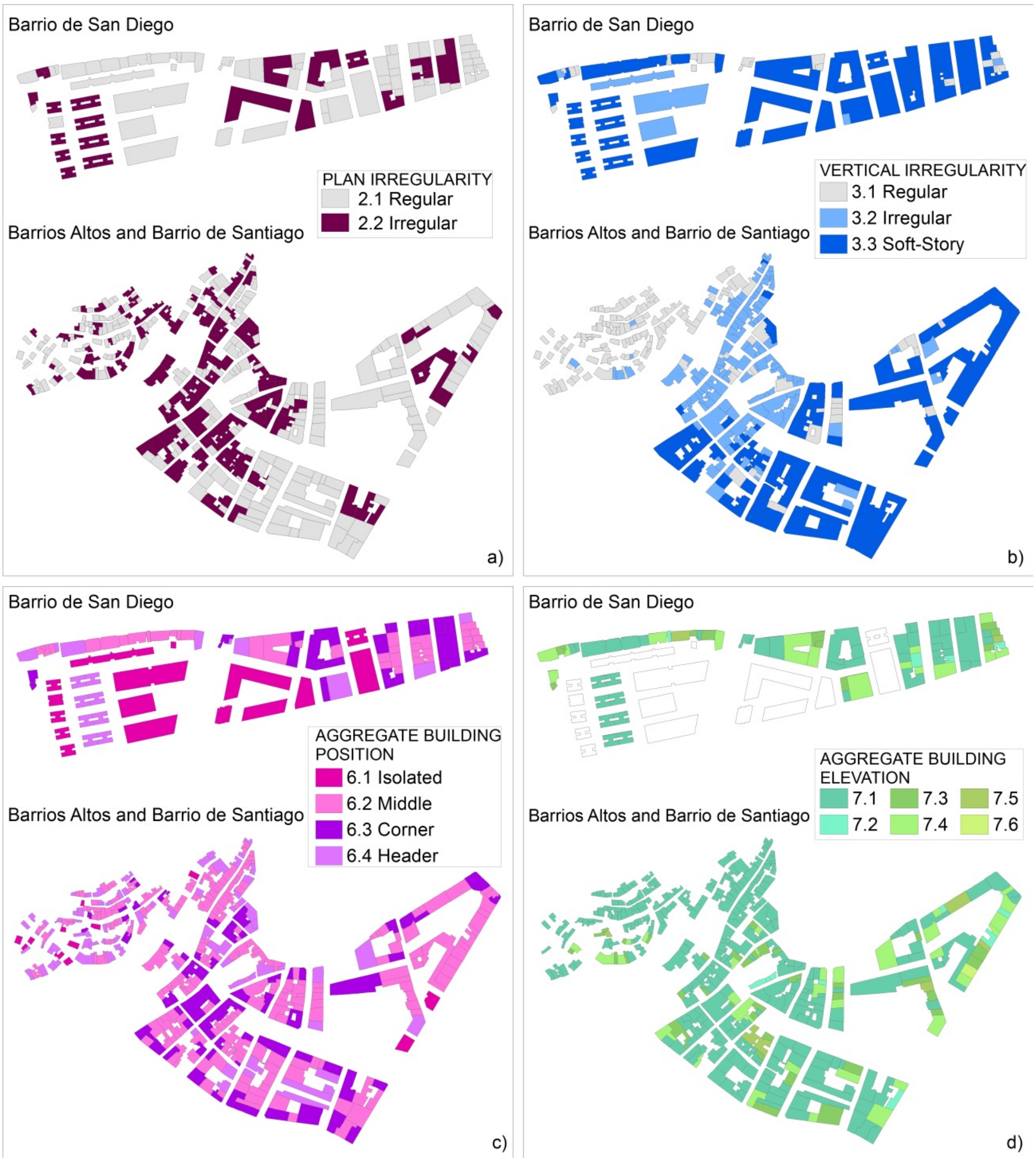


Figure 10. Geographic distribution of behavior modifiers in the study zones: a) plan irregularity, b) vertical irregularity, c) aggregate building position and d) aggregate building elevation.

Regarding the aggregated building position and elevation, *Barrio de San Diego* contains several isolated buildings and adjacent buildings usually have the same height. In turn, in the other study areas, the presence of isolated buildings is not significant null and the adjacent buildings typically present different height (Figure 10 c, d).

3.1.7. Vulnerability assessment results: Iv and EMS98 classes.

The regional modifier of seismic vulnerability is uniform for the city of Lorca and hence presents no geographical variation in the study area. The analysis of the geographical distribution of vulnerability classes will be carried out in two parts: First, the geographical distribution of the most likely I_V value plus the regional modifier is considered ($I_V^* + \Delta M_R$). Subsequently, the geographical variability of total I_V values (i. e., including all modifiers as $I_V^*+\Delta M_R + \Delta M_C$), is addressed.

Figure 11a shows that the Iv value without behavior modifiers is below 0.6 in *Barrio de Santiago and Barrio de San Diego*, and rises in *Barrios Altos*, where buildings are older and predominantly of masonry wall structure. The consideration of behavior modifiers implies a Iv variation ranging between -0.12 and +0.24. In general, an increase on seismic vulnerability is observed for all areas, being more significant for RC buildings in *Barrio de Santiago* (Figure 11b), whose structural performance approaches to the expected response of a more vulnerable class.

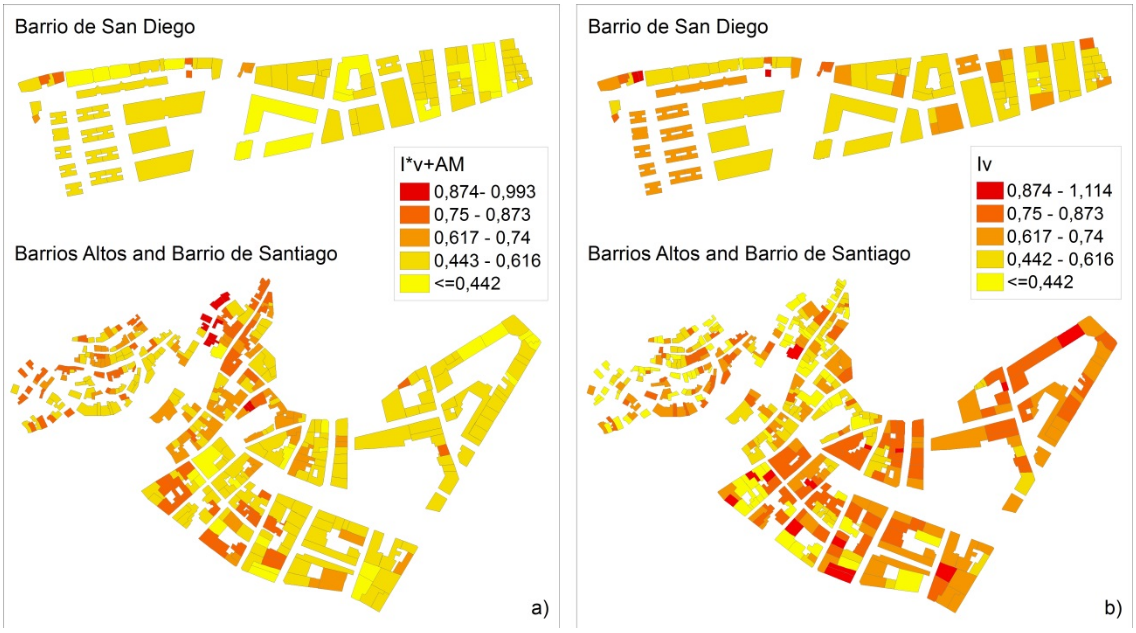


Figure 11. a) Distribution of I_V+ΔM_R values. b) Distribution of I_V=I_V*+ΔM_R+ΔM_C values.*

It is convenient to translate the I_V estimates obtained so far into the vulnerability classes defined in the European Macroseismic Scale EMS98, as most damage reports and vulnerability assessment are more easily compared using this scale. The relation between I_V values and EMS98 classes is shown in Table 3. These values are taken from the limits of plausible intervals (or I_V values for which the membership function takes the value of 0.5), as described by Milutinovic and Trendafiloski (2003). The geographical distribution of EMS98 vulnerability classes, derived by applying the correspondence of Table 3 to Figure 11**,** is represented in Figure 12).

It is observed in Figure 12 that the consideration of behavior modifiers lead to the conversion of one vulnerability class in another class of one or even two categories more vulnerable. In *Barrio de San Diego*, almost half of the buildings initially labelled as vulnerability class D pass to class C and 10% to class B. In total, the implied change of vulnerability class involves a 22% of buildings in *Barrios Altos,* a 29% in *Barrio de Santiago* and a 45% in *Barrio de San Diego*.

Table 3. Relation between Iv value and EMS98 vulnerability class (modified from Milutinovic and Trendafiloski, 2003).

EMS98 vulnerability class	Iv interval
A	> 0.82
B	(0.66,0.82]
C	(0.50,0.66]
D	(0.34,0.50]
E	(0.18,0.34]
F	< 0.18

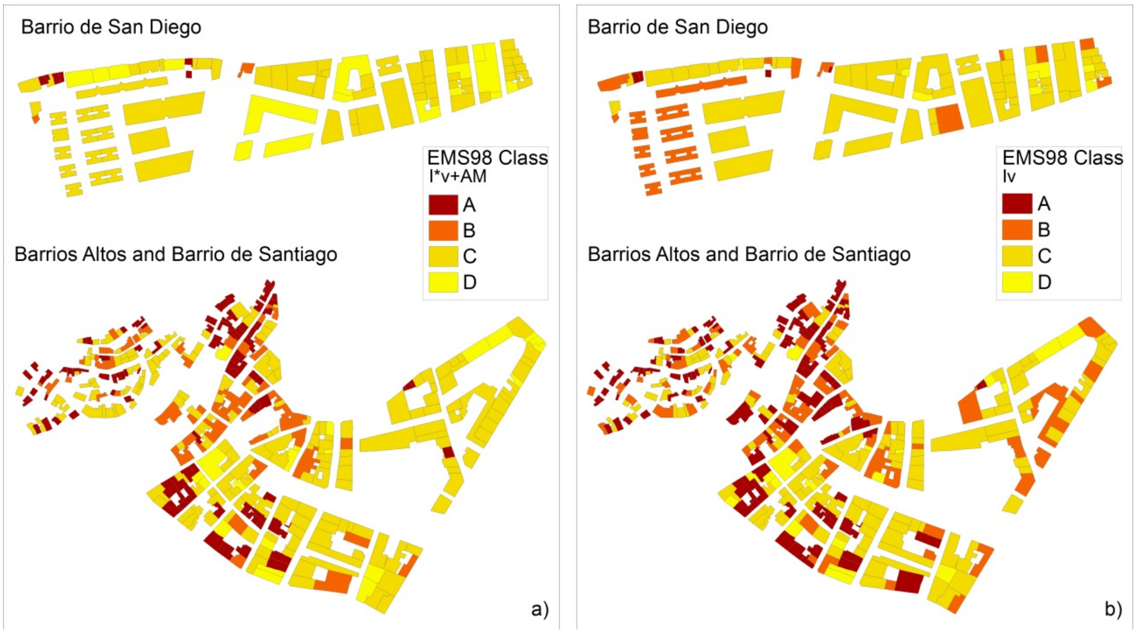


Figure 12. a) Distribution of EMS98 classes derived from I_V+ΔM_R values in zones 1 (top) and 2 (bottom). b) Distribution of EMS98 classes derived from I_V values in zones 1 (top) and 2 (bottom).*

3.2. Damage Distribution of the 2011 Lorca Earthquake

The damage assessment carried out in Lorca after the 2011 earthquake was led by the Civil Defence Department (Government Delegation in Murcia). A four-color code was used to assess building habitability since the emergency response phase and subsequent updates. Table 4 shows the equivalence between building habitability and damage to structural and non-structural building components.

Table 4. Equivalence between building habitability and damage to structural and non-structural building elements.

COLOR CODE	HABITABILITY	DAMAGE	COMMENT
Black	Forbidden access	Collapse/ Extreme	Mandatory demolition Collapse or severe damage to structural elements
Red	Forbidden access	Severe	Prohibited access because structural damage requiring repairing and retrofitting measures Loss of bearing capacity. Probably unable to withstand aftershock shaking
Yellow	Forbidden access (unless reinforced)	Moderate	Restricted access due to damage on non-structural elements. Significant reduction of bearing capacity or important damage to architectural elements
Green	Habitable	Slight	Loss of bearing capacity not apparent
White	Habitable	Very slight	Only suffered minor damage or no damage

According to the data provided by the city council of Lorca after the 2011 earthquake for the study areas, up to 57 % of the inspected buildings were classified as habitable (green code) because they did not show any damage; 21% of the buildings had forbidden/restricted access (yellow code) because they had significant non-structural damage; 17% of the building were declared not habitable (red code) due to important structural damage; and finally, 5% of the buildings were appointed for demolition (black code) due to partial collapse or extreme structural damage (*Ayuntamiento de Lorca*, 2012).

The damage distribution for all study areas gives similar percentages of severe (red) damage, around 10%. However, there are more proportion of undamaged or very slightly damaged (white) buildings in *Barrios Altos* (68 %) than in *Barrio de Santiago* and *Barrio de San Diego* (44 and 38 %, respectively). Conversely, slight (green) and moderate (yellow) damage results higher in *Barrio de Santiago* and *Barrio de San Diego* than in Barrios Altos (Figure 13).

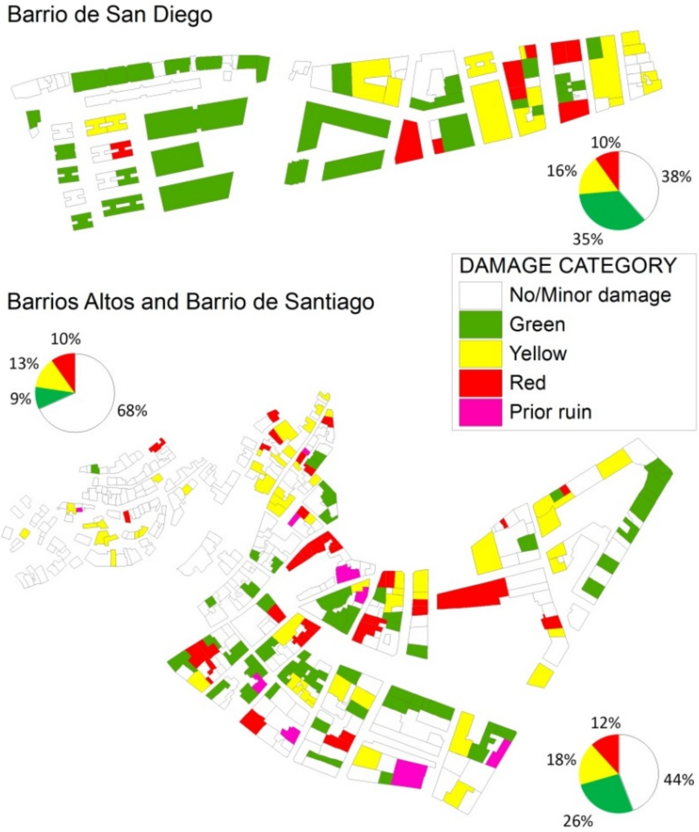


Figure 13. Geographic damage distribution and percentages in the three study areas after the 2011 Lorca quake.

4. Analysis of results. Estimation of Macroseismic Intensity.

Macroseismic intensity is basically an average estimate of damage distribution in relation to the seismic vulnerability of the exposed assets. As the distribution of vulnerability may vary significantly by considering behavior modifiers, the assessment of intensity may change accordingly in the study area. This idea is explored in order to explain the observed damage in Lorca.

Tables 5, 6 and 7 show the distribution of damage in the study areas, giving the estimate (number and percentage) of damaged buildings per vulnerability class. The percentages are useful for the comparison with the EMS98 definitions of quantity *most*, *many* and *a few*, corresponding to the percentages roughly ranging from 0 to 10-20%, from 10-20 to 50-60% and from 50-60 to 100%. In each study area, three separated estimates are provided, resulting from different approaches to estimate the *Iv* values (and the related EMS98 vulnerability classes): The first one considers the $I_V*+\Delta M_R$ value and the second full I_V ($=I_V*+\Delta M_R+\Delta M_C$) value, i. e., considering all behavior modifiers of vulnerability. A third estimate is calculated by increasing some behavior modifiers, as described below.

Table 5. Number and percentage % of buildings with different damage grades in Barrio de San Diego. Results are given in separate columns for vulnerability classes derived considering the full Iv value ($I_V = I_V* + \Delta M_R + \Delta M_C$) or excluding the behavior modifier ($I_V* + \Delta M_R$). The corresponding EMS98 descriptors of quantities are included.

San Diego							
		$I_V*+\Delta M_R$			$I_V = I_V* + \Delta M_R + \Delta M_C$		
CLASS	DAMAGE GRADE	Nº of buildings	% of buildings	Quantity EMS-98	Nº of buildings	% of buildings	Quantity EMS-98
A	1	4	100%	Most	4	100%	Most
	2	0	0.00%	None	0	0.00%	None
	3	0	0.00%	None	0	0.00%	None
	4	0	0.00%	None	0	0.00%	None
	5	0	0.00%	None	0	0.00%	None
B	1	2	33.33%	Many	12	44.44%	Many
	2	3	50.00%	Many	8	29.63%	Many
	3	1	16.67%	A few	5	18.52%	Many
	4	0	0.00%	None	2	7.41%	A few
	5	0	0.00%	None	0	0.00%	None
C	1	22	33.85%	Many	10	19.61%	Many
	2	22	33.85%	Many	27	51.92%	Most
	3	12	18.46%	Many	10	19.61%	Many
	4	9	13.85%	A Few	5	9.62%	A few
	5	0	0.00%	None	0	0.00%	None
D	1	3	18.78%	Many	5	62.50%	Most
	2	10	62.50%	Most	3	37.50%	Many
	3	3	18.75%	Many	0	0.00%	None
	4	0	0.00%	None	0	0.00%	None
	5	0	0.00%	None	0	0.00%	None

Table 6. Number and percentage % of buildings with different damage grades in Barrios Altos. Results are given in separate columns for vulnerability classes derived considering the full Iv value ($I_V = I_V^* + \Delta M_R + \Delta M_C$) or excluding the behavior modifier ($I_V^* + \Delta M_R$). The corresponding EMS98 descriptors of quantities are included.

Barrios Altos							
		$I_V^*+\Delta M_R$			$I_V = I_V^* + \Delta M_R + \Delta M_C$		
CLASS	DAMAGE GRADE	Nº of buildings	% of buildings	Quantity EMS-98	Nº of buildings	% of buildings	Quantity EMS-98
A	1	50	65%	Most	69	63.89%	Most
	2	1	1%	A few	1	0.93%	A few
	3	12	15.58%	Many	22	20.37%	Many
	4	14	18.18%	Many	16	14.81%	A few
	5	0	0.00%	None	0	0.00%	None
B	1	44	80%	Most	54	79.41%	Most
	2	3	3.64%	A few	4	5.88%	A few
	3	3	5.45%	A few	4	5.88%	A few
	4	6	10.91%	A few	6	8.82%	None
	5	0	0.00%	None	0	0.00%	None
C	1	76	57.58%	Most	52	65.82%	Most
	2	21	15.91%	Many	17	21.52%	Many
	3	30	22.73%	Many	6	7.59%	A few
	4	5	3.79%	A few	4	5.06%	A few
	5	0	0.00%	None	0	0.00%	None
D	1	1	100%	Most	6	60.00%	Most
	2	0	0.00%	None	2	20.00%	Many
	3	0	0.00%	None	2	20.00%	Many
	4	0	0.00%	None	0	0.00%	None
	5	0	0.00%	None	0	0.00%	None

Table 7. Number and percentage % of buildings with different damage grades in Barrio de Santiago. Results are given in separate columns for vulnerability classes derived considering the full Iv value ($I_V = I_V^* + \Delta M_R + \Delta M_C$) or excluding the behavior modifier ($I_V^* + \Delta M_R$). The corresponding EMS98 descriptors of quantities are included.

Barrio de Santiago							
		$I_V^*+\Delta M_R$			$I_V = I_V^* + \Delta M_R + \Delta M_C$		
CLASS	DAMAGE GRADE	Nº of buildings	% of buildings	Quantity EMS-98	Nº of buildings	% of buildings	Quantity EMS-98
A	1	5	71.43%	Most	4	66.67%	Most
	2	0	0.00%	None	0	0.00%	None
	3	0	0.00%	None	0	0.00%	None
	4	2	28.57%	Many	2	33.33%	Many
	5	0	0.00%	None	0	0.00%	None
B	1	2	28.57%	Many	14	60.87%	Most
	2	1	14.29%	A few	4	17.39%	Many
	3	1	14.29%	A few	1	4.35%	A few
	4	3	42.86%	Many	4	17.39%	Many
	5	0	0.00%	None	0	0.00%	None
C	1	33	43.42%	Many	21	32.81%	Many
	2	21	27.63%	Many	21	32.81%	Many
	3	15	19.74%	Many	16	25.00%	Many
	4	7	9.33%	A few	6	9.38%	Many
	5	0	0.00%	None	0	0.00%	None

D	1	6	46.15%	Many	7	70.00%	Most
	2	5	38.46%	Many	2	20.00%	Many
	3	2	15.38%	Many	1	10.00%	A few
	4	0	0.00%	None	0	0.00%	None
	5	0	0.00%	None	0	0.00%	None

Additionally, a figure showing the observed distribution of intensity degrees in the stud areas zones with the distribution of intensity degrees described in the EMS98 scale is included (Figure 14).This would help to infer an intensity value consistent with the EMS98 scale.

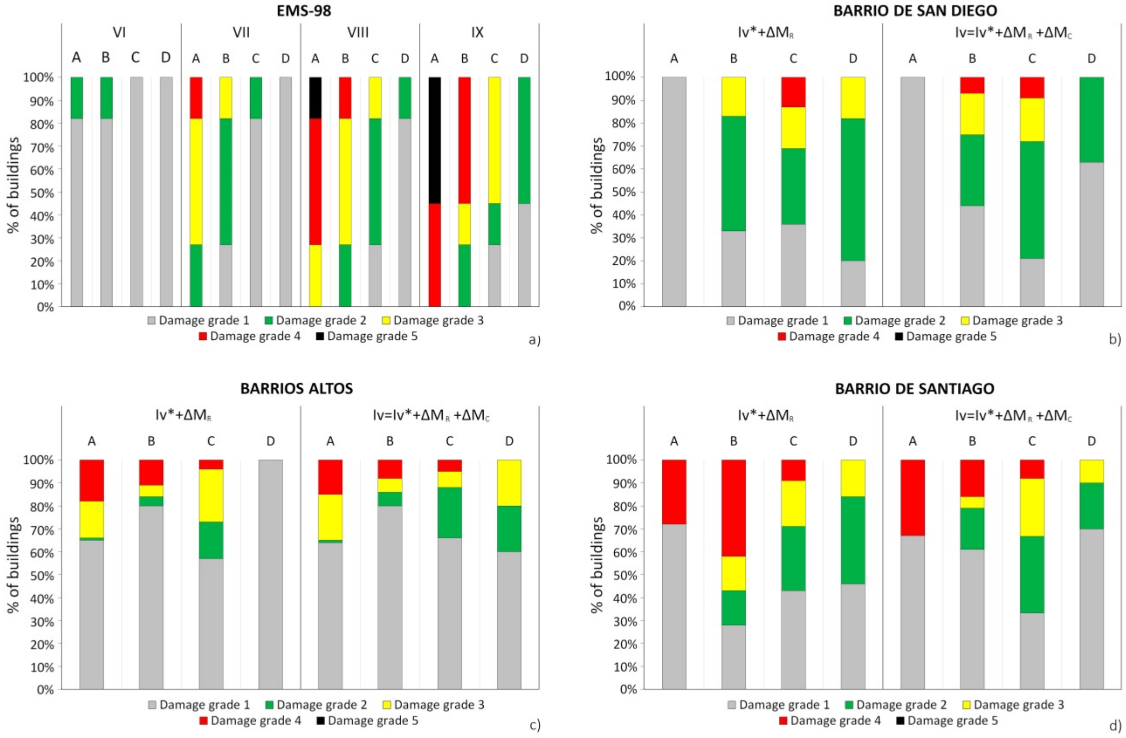


Figure 14. Damage distribution per vulnerability class (in percentages) as defined in the EMS98 scale for intensities degrees VI, VII, VIII and IX plus the damage distribution per vulnerability class, including and excluding behavior modifiers for the three study areas.

Some results of the table may be unexpected, such as the higher percentage of damage grade 1 buildings in class A buildings in comparison to class C buildings in *Barrio de San Diego* and *Barrio de Santiago*. This can be explained by the low amount of class A buildings considered, which may bias the end results. In order to avoid these misleading inferences, the intensity assessment analysis is carried out disregarding the classes with small amount of data (identified with gray color in the Tables 5, 6 and 7).

The first inference is that the resulting distribution of damage does not support an intensity VI for the study areas. Further, the analysis of results (including and excluding vulnerability modifiers) shows no clear correspondence with any intensity grade in all study areas, with the . The high incidence of damage grades 3 and 4 in class C buildings would suggest an intensity IX event. However, this is not consistent with the lower incidence of the same damage grades in class B buildings. A macroseismic intensity of VII or VIII seems to be more reasonable, especially when vulnerability modifiers are taken into account. This is most apparent for *Barrios Altos*. Nonetheless, it is still observed a relatively higher impact on class C and D buildings than in class B buildings. This could be explained by the poor performance of RC buildings with soft story, which exhibited significant damage (Romão et al., 2013; De Luca et al., 2014; Hermanns et al., 2014). This is particularly important in *Barrio de San Diego* and *Barrio de Santiago*, where RC buildings are the majority. To assess the importance in localizing damage of the vulnerability modifier related to the soft story of RC buildings (labelled 3.3 in Table 2), the previous analysis is repeated for all areas with an increase of +0.2 in this modifier.

The results are presented in Table 8. The significant increase on the modifier implies a general shift of buildings toward higher vulnerability classes. The resulting percentage of buildings that change of vulnerability class are 59% of buildings in *Barrios Altos,* 78% in *Barrio de Santiago* and 74% in *Barrio de San Diego*. According to this approach, most buildings lie in vulnerability classes A and B. The analysis is then focused in the damage distribution of these vulnerability classes. As observed in Figure 15, the distributions of damage in all areas follow a more common pattern, in which the classes that are more vulnerable exhibit more damage and, within a given class, there are lesser buildings with damage grade 4 than buildings with lower damage grades.

Table 8. Number and percentage % of buildings with different damage grades for the three study areas. Results are given in separate columns for vulnerability classes derived considering value Iv+0.2.

		Barrio de San Diego		**Barrios Altos**		**Barrio de Santiago**	
		$I_V+0.2$		$I_V+0.2$		$I_V+0.2$	
CLASS	DAMAGE GRADE	Nº of buildings	% of buildings	Nº of buildings	% of buildings	Nº of buildings	% of buildings
A	1	10	33%	139	69%	20	47%
	2	8	27%	10	5%	12	28%
	3	7	23%	30	15%	5	12%
	4	5	17%	23	11%	6	14%
	5	0	0%	0	0%	0	0%
B	1	17	37%	37	66%	17	40%
	2	19	41%	13	23%	13	30%
	3	7	15%	3	5%	9	21%
	4	3	7%	3	5%	4	9%
	5	0	0%	0	0%	0	0%
C	1	5	42%	5	71%	5	38%
	2	5	42%	1	14%	2	15%
	3	1	8%	1	14%	4	31%
	4	1	8%	0	0%	2	15%
	5	0	0%	0	0%	0	0%
D	1	0	19%	0	0%	3	100%
	2	0	63%	0	0%	0	0%
	3	0	19%	0	0%	0	0%
	4	0	0.00%	0	0%	0	0%
	5	0	0%	0	0%	0	0%

Still, the assessment of a macroseismic intensity degree for each study area is not evident. If the damage distribution of class A buildings is observed, an intensity degree of VII could be assigned to all study areas. In turn, if the damage distribution of class B buildings is considered, an intensity degree of VIII could be suggested.

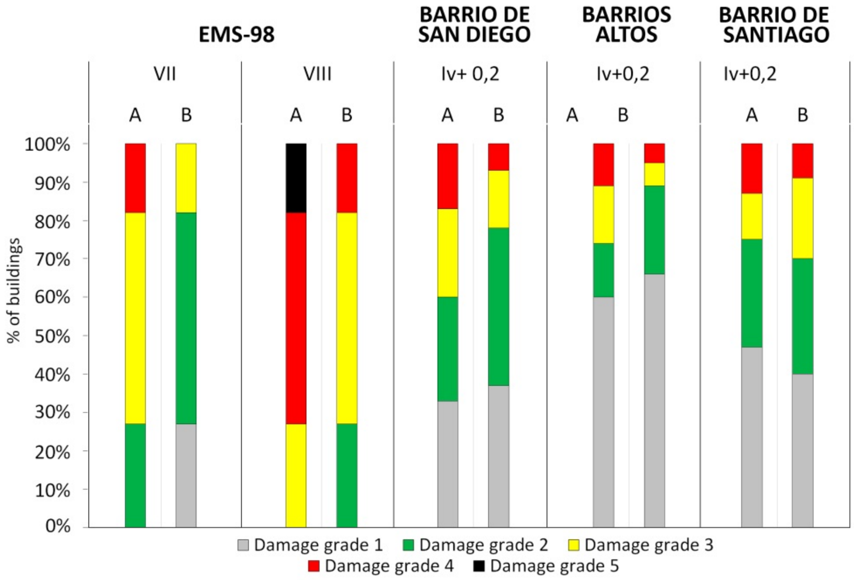


Figure 15. Damage distribution per vulnerability class A and B (in percentages) as defined in the EMS98 scale for intensities degrees VII and VIII plus the damage distribution per these vulnerability classes, including and excluding behavior modifiers for the three study areas.

5. Discussion and conclusions

The 2011 Lorca earthquake produced significant damage, especially for a relatively small event of Mw magnitude 5.2. A macroseismic instensity of VII was estimated by the Spanish Instituto Geografico Nacional for the mainshock (Cabañas et al., 2011). A factor contributing to reach this value was the high ground motions produced, which were related to the near source effects (Benito et al. 2012; Alguacil et al., 2013), including rupture directivity (López Camino et al. 2012) and the shallow location of the hypocenter (Cabañas et al., 2011). Resonant effects enhanced this ground motion for particular soil conditions in several locations of Lorca and building predominant vibration periods (Navarro et al., 2013, Vidal et al., 2013; Belvaux et al. 2014). This effect was quantified in an increment of half a grade of macroseismic intensity for softer soils and a decrement of half a grade for rock sites by Figueras et al. (2012). Additionally, seismic vulnerability exerted a prime control on damage distribution. Thus, the poor performance of RC buildings with masonry infills and with soft story buildings was observed by many authors (Donaire-Dávila et al, 2012; Benavent-Climent et al., 2014; De Luca et al. 2014; Hermanns et al. 2014), and contrasts with the relatively good performance of unreinforced masonry structures (e. g., Basset-Salom and Guardiola-Víllora, 2014).

The present study focuses on the vulnerability assessment, including the effect of vulnerability modifiers that help to explain the distribution of damage by redefining the vulnerability class of certain building typologies as shown by Martinez-Cuevas el al. (2015). Feriche et al. (2012) also considered vulnerability modifiers estimated from open databases and increased to assess damage observations after the Lorca event. They developed several scenarios and compared the expected mean damage for different intensity values (here considering the intensity as ground motion parameter), suggesting a best scenario for intensity VII in harder soils sites and VIII in softer sites. In this study, the vulnerability assessment is refined using an important amount of data collected on site, and the macroseismic intensity is reassessed in order to explain the observed data. It is worth noting that a significant increase on the vulnerability behavior modifier related to soft story in RC buildings is required to explain the observed damage patterns in concordance with the EMS98 descriptions of intensity. This implies that a significant amount of buildings initially assigned a vulnerability class C are reassigned to higher vulnerability classes. According to this approach, the damage distribution of class A and class B buildings points to an intensity VII and VIII, respectively.

Previous studies (e. g., Rivas-Medina et al., 2013; Salgado et al., 2015) showed the difficulties for reproducing the damage distribution observed in Lorca after the 2011 event. This was partly due to the unavailability of fragility curves accounting for non-structural components that have a significant effect on building performance (category A of D'Ayala et al., 2015), which produced larger damage on older, more vulnerable areas of the city (as *Barios Altos*) than the more modern areas. The incorporation of vulnerability modifiers into fragility curves could contribute to minimize them.

A final remark of this study is the importance of incorporating the performance of non-structural building components and urban parameters in procedures for vulnerability assignment and damage assessment. This idea is integrated in developing initiatives such as the Global Earthquake Model Vulnerability group and the International Macroseismic Scale (Porter et al. 2012; Spence and Foulser-Piggott, 2014).

Acknowledgements

This work is partly developed in the frame of the MERISUR project; *reference CGL2013-40492-R, Programa Estatal de Investigación, Desarrollo e Innovación Orientada a los Retos de la Sociedad, Ministerio de Economía y Competitividad* of Spain.

References

Alguacil G, Vidal F, Navarro F, García-Jerez A, Pérez-Muelas J (2014). Characterization of earthquake shaking severity in the town of Lorca during the May 11, 2011 event. Bull Earthquake Eng 12: 1889-1908.

Ayuntamiento de Lorca , 2012. "Visor geográfico seismo de Lorca de 11 de mayo de 2011". http://www.lorca.es/ficheros/file/sitLorcaSeismo/index.asp. Accessed on June 22, 2015.

Basset-Salom L, Guardiola-Víllora A (2014). Seismic performance of masonry residential buildings in Lorca's city centre, after the 11thMay 2011 earthquake. Bull Earthquake Eng 12:2027-2048.

Belvaux M, Macau A, Figueras S, Goula X, Susagna T (2014) Recorded ground motion and estimated soil amplification for the May 11, 2011 Lorca earthquake. Earthquake Spectra, in press

Benavent-Climent A, Escobedo A, Donaire-Avila J, Oliver-Saiz E, Ramírez-Márquez AL (2014). Assessment of expected damage on buildings subjected to Lorca earthquake through an energy-based seismic index method and nonlinear dynamic response analyses. Bull Earthquake Eng 12: 2049-2073.

Benedetti D, Petrini V (1984). Sulla vulnerabilità di edifici in muratura: proposta di un metodo di valutazione, L'industria delle Costruzioni 149: 66-74.

Benito B, Rivas Medina A, Gaspar-Escribano JM, Murphy P (2012). El terremoto de Lorca (2011) en el contexto de la peligrosidad y el riesgo sísmico en Murcia. Física de la Tierra 24, 255-287.

Cabañas L, Alcalde JM, Carreño E, Bravo JB (2014) Characteristics of observed strong motion accelerograms from the 2011 Lorca (Spain) Earthquake. Bull Earthquake Eng 12: 1909-1932.

CCS, Consorcio de Compensación de Seguros (2014). La Cobertura de los Riesgos Extraordinarios en España. Ed Consorcio de Compensación de Seguros, 16 pp.

D'Ayala D, Meslem A, Vamvatsikos D, Porter K, Rossetto T (2015) Guidelines for Analytical Vulnerability Assessment of Low/Mid-Rise Buildings, Vulnerability Global Component Project.

De Luca, F., Verderame, G.M., Gómez Martínez, F., Pérez García, A. (2014). The structural role played by masonry infills on RC building performances after the 2011 Lorca, Spain, earthquake. Bull Earthquake Eng, 12: 1999-2026.

Donaire-Avila J, Benavent-Climent A, Escobedo A, Oliver-Saiz E, Ramírez-Márquez AL, Feriche M (2012). Damage assessment on building structures subjected to the recent near-fault earthquake in Lorca (Spain). 15 World Conference on Earthquake Engineering. Lisbon, Portugal.

Grünthal G (1998). European Macroseismic Scale 1998. Cahiers du Centre Européen de Géodynamique et de Séismologie 15: 100 pp.

Feriche M, Vidal F, Alguacil G, Navarro M, Aranda C (2012). Vulnerabilidad y Daño en el Terremoto de Lorca de 2011. Vulnerability and Earthquake Damage in Lorca 2011. 7ª Asamblea Hispano Portuguesa de Geodesia y Geofísica, Donosti, San Sebastián, España, 2012.

Figueras, S., Macau, A., Peix, M., Benjumea, B., Gabas, A., Susagna, T., & Goula, X. (2012). Caracterización de efectos sísmicos locales en la ciudad de Lorca. Física de la Tierra, 24, 235-254.

IGN (2011) Informe del sismo de Lorca de mayo de 2011. Instituto Geográfico Nacional. 138pp. http://www.ign.es/ign/resources/sismologia/Lorca.pdf

López-Comino JA, Mancilla FL, Morales J, Stich D (2012). Rupture directivity of the 2011, Mw 5.2 Lorca earthquake (Spain). Geophys Res Lett 39.

Lantada N, Irizarry J, Barbat AH, Roca A, Susagna T, Pujada LG (201o). Seismia hazard and risk scenarios for Barcelona, Spain, using the Risk-UE Vulnerabilitu¡y index method.Bull Earthquake Eng 01/2010.

Martínez-Cuevas S, Cervera J, Benito B, Morillo MC, 2015. Methodology to identify urban parameters that influences seismic vulnerability. Exploratory study of the city of Lorca 2011. (Submitted to BEEE).

Milutinovic ZV, Trendafiloski GS (2003) RISK-UE, An advanced approach to earthquake risk scenarios with applications to different European towns. Report to WP4: Vulnerability of current buildings, 109 pp

Morales J, Cantavella JV, Mancilla FL, Lozano L, Stich D, Herraiz E, Martín JB, Lopez-Comino JA, Martinez-Solares JM (2014). The 2011 Lorca seismic series: Temporal evolution, faulting parameters and hypocentral relocation. Bull Earthquake Eng 12: 1871-1888.

Navarro M, García-Jerez A, Alcalá FJ, Vidal F, Enomoto F (2014) Local site effect microzonation of Lorca town (SE Spain). Bull Earthquake Eng 12: 1933-1959.

Porter K, Greene M, Jaiswal K, Wald DJ (2008). WHE-PAGER project: A new initiative in estimating global building inventory and its vulnerability, in Proceedings of the 14th World Conference on Earthquake Engineering, Beijing, China, 8 pp.

Porter, K.A., Farokhnia, K., Cho, I.H., Rossetto, T., Ioannou, I., Grant, D., Jaiswal, K., Wald, D., D'Ayala, D., Meslem, A., So, E., Kiremidjian, A.S. and Noh, H. (2012), Global Vulnerability Estimation Methods for the Global Earthquake Model, Proceedings of the 15th World Conference on Earthquake Engineering, Lisbon.

Romão, X., Costa, A. A., Paupério, E., Rodrigues, H., Vicente, R., Varum, H., & Costa, A. (2013). Field observations and interpretation of the structural performance of constructions after the 11 May 2011 Lorca earthquake. Engineering Failure Analysis, 34, 670-692.

Salgado-Galvez, M.A., Cardona, O.D., Carreño, M.L. and Barbat, A.H. (2015). Probabilistic seismic hazard and risk assessment in Spain. Monografía CIMNE IS 69.

Santoyo MA (2014) Finite fault analysis and near-field dynamic strain and rotation estimates due to the 11/05/2011 (Mw5.2) Lorca earthquake, south-eastern Spain. Bull Earthquake Eng 12: 1855-1870.

Spence R, Foulser-Piggott R (2014). The International Macroseismic Scale - Extending EMS-98 For Global Application. Second European Conference on Earthquake Engineering and Seismology, Istanbul, Turkey.

F. Vidal, M. Navarro, C. Aranda, T. Enomoto (2013) Changes in dynamic characteristics of Lorca RC buildings from pre- and post-earthquake ambient vibration data. Bull Earthquake Eng 12: 2095-2110.