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ORIGINAL RESEARCH PAPER

Seismic performance of masonry residential buildings in Lorca's city centre, after the 11th May 2011 earthquake

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Abstract Lorca May 11, 2011 earthquake, whose magnitude and intensity reached Mw = 5.1 and I = VII, caused heavy damages, showing the vulnerability of masonry historic buildings and reinforced concrete improper designed structures. The main objectives of this paper are to study the seismic response of unreinforced masonry residential building stock in Lorca historic centre and to compare it with the vulnerability and feasible collapse mechanisms predicted by the FaMIVE Method (D'Ayala and Speranza in Proceedings of 12th European conference of earthquake engineering. Elsevier Science Limited, London, 2002; Earthq Spectra 19(3):479–509, 2003), which has been proved to be accurate in the description and prediction of damages in this type of structures. For this purpose, three onsite surveys were carried out, in May, June and December 2011, on a sample of the masonry residential buildings in Lorca historic centre (area included in the Special Protection and Rehabilitation Plan of the Historic and Artistic Site of Lorca). Information regarding geometry, quality of materials, structure and construction characteristics was collected, establishing the observed collapse mechanisms and evaluating rigorously damage and crack patterns. Google Street View was used for the analysis of the state of the buildings before the earthquake. These buildings were then assessed and mapped using a GIS system. Results provided good accordance with the observed data, showing, at the same time, very different building seismic performance. Effective connections between façades and party walls, a good maintenance level of masonry and roofs and the use of specific reinforcement elements have proved to be relevant factors in lowering the vulnerability and improving the seismic behaviour of unreinforced masonry structures in Lorca historic centre.

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1 Introduction

Lorca is an ancient city located within a moderated seismic region in southeast of Spain. It is characterized by a very rich historic heritage including not only monumental or religious buildings (towers, mansions, palaces, churches or monasteries) but also a residential stock varied in age and styles.

Its seismic activity has been documented from historical sources since 343 BC (Martínez-Solares and Mezcua-Rodriguez 2002) and from instrumental sources since 1920 (IGN 2012), being the most important earthquakes in 1579, 1674, 1818, 1911, 1948, 1999, 2002 and 2005 (Cabañas et al. 2011). The occurrence of the last earthquakes increased the seismic hazard and seismic risk studies of the area (Murphy 1999; Buforn et al. 2005; Gaspar-Escribano et al. 2005, 2008; Gaspar-Escribano and Benito 2007). Within this context the RISMUR project (Seismic Risk Assessment of the Murcia Region) was led and financed by the national and local government. Its final report (Benito et al. 2006) considered Lorca one of the cities within the Murcia Region with higher seismic risk, due mainly to its proximity to the active *Alhama de Murcia Fault* (AMF), providing recommendations for future developments in order to define risk reduction measures.

As many of the European historic centres in seismically active areas, Lorca's city centre consists of a residential and commercial district with a majority of the buildings made of unreinforced stone or brick masonry, often with a bad level of maintenance. Despite of the Special Protection and Rehabilitation Plan of the Historic and Artistic Site of Lorca, PEPRI, (Lorca's City Council 2000), some of the buildings have been allowed to decay. On the other hand, there hasn't been any explicit concern to earthquake protection in this area: except for the use of ring beams, quoins or iron ties in a small number of buildings, there has been hardly any upgrading intervention to improve their seismic vulnerability.

On May 11th 2011, at 16:47:25, a moderate earthquake of magnitude $Mw = 5.1$, with shallow focal depth (3 km), struck Lorca, being considered the worst earthquake to hit Spain in the last 50 years. This earthquake caused nine casualties and produced damage of different grades in 80 % of the buildings, including all the churches, monasteries and historical buildings.

A large number of instrumental strong motion records were available, regarding the foreshocks, mainshock and aftershocks, providing data to Spanish and European researchers who came to Lorca to observe directly the damage and to study the effects on recent and historic structures.

Buildings and historical heritage were heavily damaged by the earthquake. More than 7,800 buildings were inspected in the aftermath of the event (Goula et al. 2011) and preliminarily classified by colours, according to the safety and the observed damages (Fig. 1).

Notwithstanding the effects of this earthquake on reinforced concrete buildings (one collapsed during the event), the main objective of this paper is to study the seismic response of unreinforced masonry buildings in Lorca historic city centre sector II, area included in the PEPRI. The fact that, after this event, some of the listed buildings (Catalogue of Protected Buildings 1994) have been demolished, leaving only, in some cases, their façades with underpinnings (Guardiola-Víllora and Basset-Salom 2012), shows the necessity of assessing the vulnerability of buildings in historic centres to establish improving and strengthening strategies in order to reduce future earthquake damage, to prevent unnecessary demolitions and to preserve the cultural value of historical heritage.

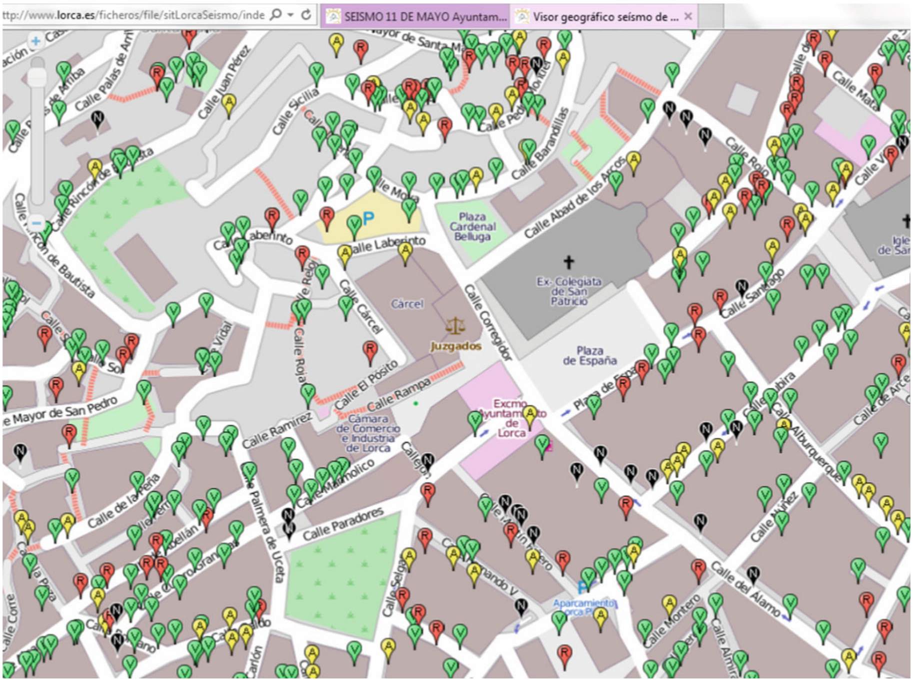


Fig. 1 Damage building location and classification: *Black*, N (collapsed or to be demolished, 4.2 %), *red*, R (significant structural damage, 8.85 %), *yellow*, A (low to moderate structural damage, significant to moderate non-structural damage, 17.08%) and *green*, V (without structural damage, low to moderate non-structural damage, safe for normal use, 69.87%). *Source*: Lorca's City Council 2011

The study described in this paper started with three on site surveys after the 11th May 2011 Lorca earthquake, in May, June and December 2011. Assuming that the most vulnerable wall plane of a masonry building is the façade, detailed visual data from 65 façades were collected and organised in a data base, including geometrical parameters, masonry materials, boundary conditions, construction and structural characteristics, specific strengthening devices, conservation status and observed damages. A special attention was made to establish clearly the building damages produced by the earthquake, comparing the building characteristics before and after the event (pictures from Google Street View 2009).

To quantify the seismic vulnerability, the Failure Mechanisms Identification and Vulnerability Evaluation procedure, FaMIVE, has been adopted (D'Ayala and Speranza 2002, 2003). This method, based on a limit state analysis and lower bound approach, follows the methodology developed for vulnerability assessment of masonry buildings belonging to historic city centres in Europe. It has also been applied in the description and definition of damage scenarios in Asia (D'Ayala 2003, 2006; D'Ayala and Ansal 2009) and in the analysis of damage in L'Aquila historic centre after 2009 earthquake (D'Ayala and Paganoni 2011).

FaMIVE identifies all the feasible collapse mechanisms for each masonry façade considering the specific characteristics provided by an in situ survey (masonry typology and quality, façade geometry and structural characteristics, constraint and connection conditions, etc.) and evaluates their associated ultimate load factor (expressed by the index ESC, equivalent shear capacity, in terms of percentage of gravity acceleration). Then, among all the possible mechanisms for each façade, the "worst" is selected as the prevalent one, depending on the associate ultimate load factor and the damage extent (façades, walls and floor structures involved in

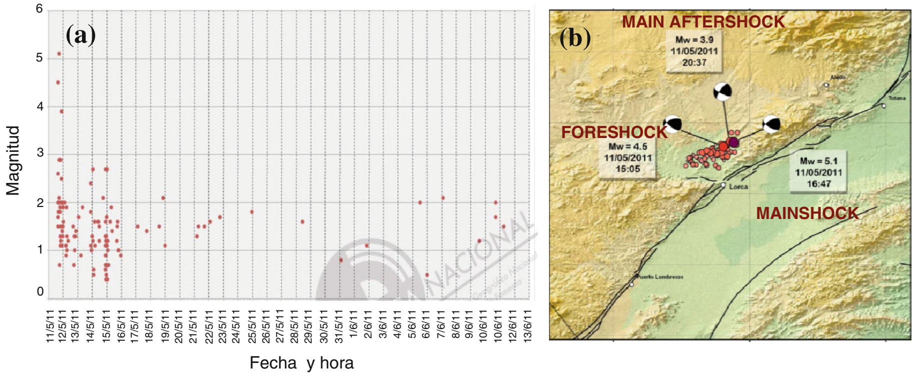


Fig. 2 **a** Earthquake sequence (IGN 2011) and **b** location of the foreshock, mainshock and main aftershok (Cabañas et al. 2011)

the collapse), obtaining the corresponding value of the seismic vulnerability. When for two or more feasible mechanisms the ultimate load factor and damage extent have similar values, FaMIVE predicted mechanism will be the one with the most damaging consequences.

Finally each building is ascribed to one of the four normalised vulnerability classes: *low*, *medium*, *high* and *extreme* (D'Ayala 2005).

A correlation between observed data collected from the field survey and FaMIVE results (both displayed with a Geographical Information System) has been established in terms of failure mechanisms and damage level.

2 Lorca earthquake characteristics

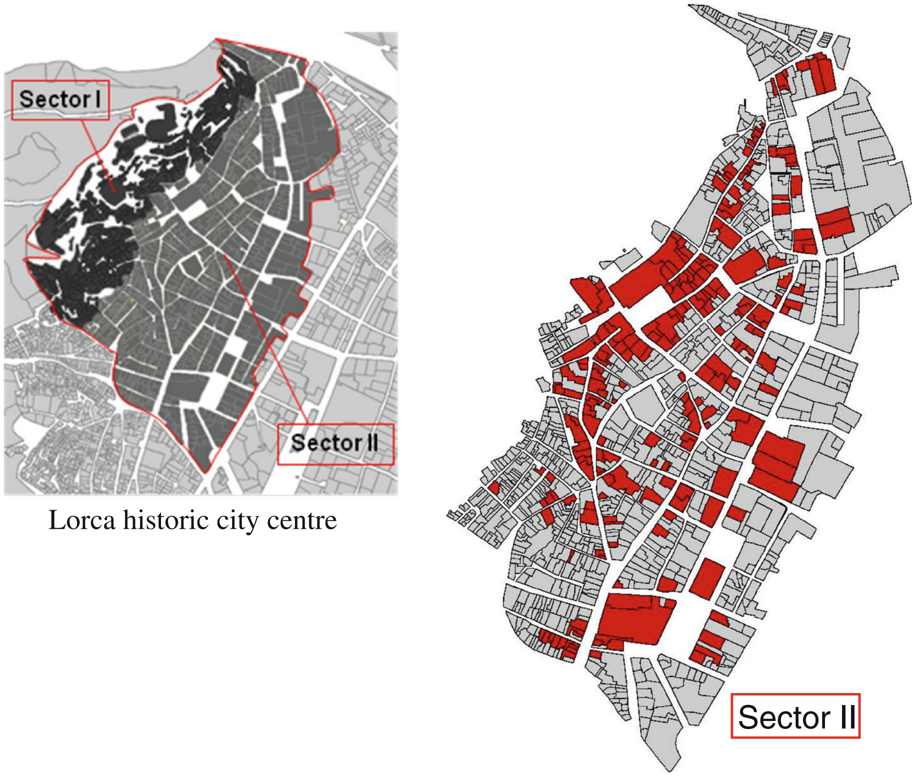
Preceded by a Mw = 4.5 foreshock at 15:05:13 (lat: 37041 N, long: 16812 W) and six tremors including a Mw = 2.6, the Mw = 5.1 mainshock (lat: 376946 N, long: 16756 W, 2 km NE historic city centre) was the strongest of a sequence of earthquakes that finished on July 14th, after a distribution of 135 aftershocks (Fig. 2), including a Mw = 3.9 and a Mw = 2.9 (IGN 2011).

The cause of this sequence of earthquakes has been the rupture of the well known *Alhama de Murcia Fault* which developed in the direction of the city, just below it.

The seismic intensities (EMS) for the foreshock and mainshock were very high, VI and VII (Cabañas et al. 2011), being the maximum recorded Peak Ground Acceleration 0.29 and 0.37 g, respectively. These high values (two or three times higher than the ones provided by the Spanish Seismic Code for Lorca) and the very intense effects can be explained (Benito et al. 2012) attending to the soil amplification and to the location of both epicentres: very close to the city (3.5 and 3 km to Lorca seismic station) and to the surface (2 and 3 km).

3 Lorca field survey

Lorca historic centre was one of the first to be declared as historic artistic site in Spain (1964), although the Special Protection and Rehabilitation Plan of the Historic and Artistic Site of Lorca, PEPRI (Lorca's City Council 2000), was drafted in 2000. The city was seriously damaged by the strong 1674 earthquake (Muñoz-Clares et al. 2012) which was the starting point of a long period of reconstruction: most of the building stock of the city centre, the monumental buildings and its actual urban structure belong to the following 200 years.



Lorca historic city centre

Fig. 3 Area covered by the study with the listed buildings in red (sector II)

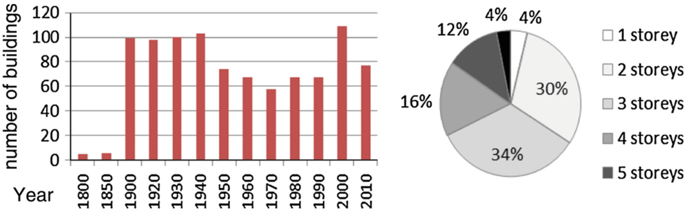


Fig. 4 Building ages (cadastral database 2011) and number of storeys

During the three on-site visits to Lorca, the authors carried out a rigorous post-earthquake field survey of the area included in the PEPRI (city centre sector II), focusing on residential unreinforced masonry (URM) buildings, as part of the historic fabric of Lorca's city centre. The area covered by the study, the average age of the buildings (43 % from 70 to 110 years old) and its heights (1–4 storeys for URM buildings and 5–6 for RC buildings) are shown in Figs. 3 and 4.

The urban layout of this area results in irregular blocks, subdivided into plots of different dimensions and different street fronts, depending mainly on the street location. The building stock is very heterogeneous: (a) full restored and well maintained mansions with residential or administrative use, (b) traditional masonry residential buildings with different levels of maintenance, (c) new apartment dwellings replacing the inside of a traditional building but keeping the original masonry façades without structural use, (d) cleaned up buildings with

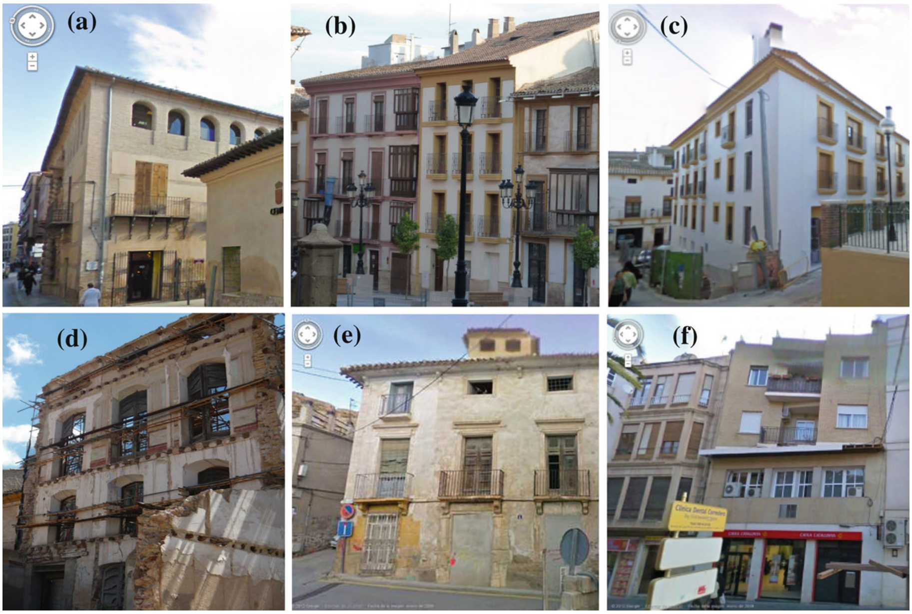


Fig. 5 Buildings in the surveyed area, before the earthquake: **a** fullrestored mansions with residential or administrative use, **b** traditional residential buildings, **c** new apartment dwellings, **d** cleaned up buildings, **e** abandoned buildings and **f** new reinforced concrete buildings (Google Street View)

braced façades, (e) abandoned buildings waiting to be declared ruined and (f) new reinforced concrete buildings built from 1970 to 2000 (see Fig. 5).

3.1 Common design practice for residential masonry buildings: constructive aspects

The vertical structural system of traditional URM residential buildings in Lorca consists of load bearing orthogonal walls forming the street façades (or the main façade and the interior courtyard façade) and the party walls (Fig. 6). Sometimes, depending on the building plan, there are interior walls with structural function.

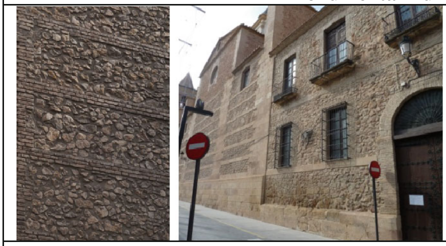
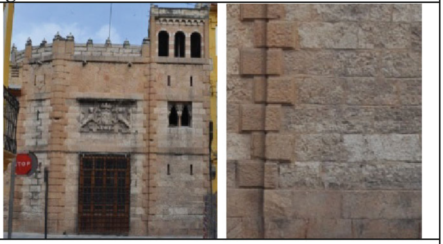
According to the direction of the horizontal structure, the thickness of the façades walls ranges from 30 to 80 cm having, sometimes, significant windows and balconies; whereas the thickness of the walls between adjacent buildings ranges from 20 to 30 cm. Generally, interior walls are thinner and usually poorly connected to exterior and party walls.

Masonry typologies recorded in the area are shown in Table 1. In XVIII and XIX centuries, masonry fabric was made out of random rubble or poorly cut stone (small or medium sized) with lime mortar, improving its quality with time. The use of brick masonry with lime or cement mortar became common along the nineteenth century, increasing the height from one or two up to four storeys (Murphy 2006). Typical size of bricks is 20 × 10 × 3/4 cm (before 1950) or 24 × 12 × 4/5 cm. There are also a few examples of random rubble stone masonry with binding brick courses. The use of regularly dressed well squared and graded stones blocks was reduced to monumental buildings and mansions while large squared stone blocks are used for quoins and plinths.

The original horizontal structures are made of timber beams for lintels, beams and joists with lightweight masonry vaults in floors or with a traditional covering made out of a reed

Fig. 6 Vertical load-bearing masonry walls: street façades and party walls

Table 1 Masonry fabric typologies in the surveyed area

Residential Buildings	
	
Rubble masonry fabric	Brick masonry fabric
Monumental Buildings and Mansions	
	
Brick and rubble masonry fabric	Stone masonry fabric

and plaster deck (named "*cañizo*") or a brick deck under ceramic curved tiles in roofs. Recent floors are made of RC beams and joists with ceramic vaults (Fig. 7). Floors and roofs are carried out either in the façades and the inner walls or in the party walls.

Frequently, buildings in a block share the party walls, presenting also a continuity of the horizontal structure and the roof overhang, either because they were built at the same time or because new buildings in between two older ones used the existing walls (Fig. 8). In these situations attention has been paid to possible coupling effects, considering buildings together instead of individually.

Fig. 7 Horizontal structures: **a** timber floors (timber beams and joists with lightweight masonry vaults), **b** roofs (reed and plaster deck, "*cañizo*", under ceramic curved tiles) and **c** new RC floors (RC beams and joists with ceramic vaults)

Fig. 8 Shared party walls

Fig. 9 Reinforcement elements: **a** quoins, **b** plinths, **c** floor and wall timber ties or timber ring beams, **d** timber lintels, **e** stone frames around openings and **f** iron ties

When adjacent buildings have independent party walls with floor and roof at different levels, they behave separately. As block heights are variable, the risk of pounding effects is not negligible and has been considered in the analysis of observed damages.

Being Lorca in a region of moderate seismicity, some reinforcement elements can be found: stone quoins in one or more storeys, plinths, floor and wall timber ties or timber ring beams placed horizontally in the middle of the thickness of the wall, timber lintels, stone frames around openings and a few iron ties connecting the façades to the floors or to the orthogonal walls (Fig. 9).

Table 2 Maintenance level of the surveyed traditional residential buildings, before the earthquake (Google Street View)

		
Good maintenance level: Neither cracks nor moisture	**Medium maintenance level:** Slight cracks in the plaster, a few roof tiles are broken or have fallen off	**Bad maintenance level:** Cracks in walls**,** mortar loss, partial failure of roof overhang, moisture and efflorescence in walls, water infiltration.

Traditional masonry residential buildings showed big differences in their maintenance level (see description in Table 2). This aspect is a determinant factor in their seismic response, not only for the building itself, but also due to the lack of the stabilizing contribution of neighbouring cells (Carocci and Lagomarsino 2009; Basset-Salom and Guardiola-Víllora 2013). The majority of the observed masonry façades, 58 %, have a good maintenance level, 30 % medium and only 12 % bad, corresponding to abandoned buildings.

3.2 Description of observed damage

As a result of the field survey, damage observed for masonry buildings within the Lorca city centre was interpreted by the authors in terms of collapse mechanisms. Then, a damage grade (from 1 to 5) was assigned to each one, according to EMS-98 for masonry structures (Grünthal 1998), taking into account structural and nonstructural damage (Fig. 10). Mechanisms were classified using the updated catalogue of mechanisms (see sketches in Fig. 11) originally developed for the FaMIVE procedure by D'Ayala and Speranza (2002, 2003). This first qualitative analysis of the whole area is materialized, quantified and detailed for the surveyed sample in Sect. 4.

Two classes of collapse mechanisms have been observed and recorded: out-of-plane mechanisms and in-plane mechanisms.

When masonry walls are subjected to horizontal actions orthogonal to their plane, out-of-plane mechanisms are likely to occur, causing a partial or total overturning of the façade, depending on the boundary conditions (connection between walls or between walls and floors, presence of strengthening elements like ties, quoins or ring beams), masonry fabric quality, wall geometry, opening layout, floor orientation, state of preservation, etc.

Examples of the different types of out-of-plane mechanisms recorded along the surveyed area are shown in Fig. 12a.

When the connection at the edges between the façade and the orthogonal walls or floors is poor or non-existent, the vertical overturning mechanism involves only the façade (totally, mechanism A, or partially, mechanism D), leaving the party walls in place. In some cases, pounding is also one of the causes of the detachment, increasing when there is a significant height difference between adjacent buildings.

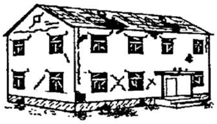
(a) Classification of damage to masonry buildings		**(b) Buildings in the area**
	**Grade 1: Negligible to slight damage (no structural damage, slight non-structural damage)** Hair-line cracks in very few walls. Fall of small pieces of plaster only. Fall of loose stones from upper parts of buildings in very few cases	
	**Grade 2: Moderate damage (slight structural damage, moderate non-structural damage)** Cracks in many walls. Fall of fairly large pieces of plaster. Partial collapse of chimneys.	
	**Grade 3: Substantial to heavy damage (moderate structural damage, heavy non-structural damage)** Large and extensive cracks in most walls. Roof tiles detach. Chimneys fracture at the roof line; failure of individual non-structural elements (partitions, gable walls).	
	**Grade 4: Very heavy damage (heavy structural damage, very heavy non-structural damage)** Serious failure of walls; partial structural failure of roofs and floors.	
	**Grade 5: Destruction (very heavy structural damage)** Total or near total collapse.	Not observed

Fig. 10 **a** Classification of damage to masonry buildings (Grünthal 1998) and **b** examples of buildings in the surveyed area with each damage grade

However, when there is an effective connection between orthogonal walls, instead of the occurrence of an in-plane mechanism, an out of plane overturning movement starts with the appearance of a diagonal crack at the top part of the party wall (overturning with one

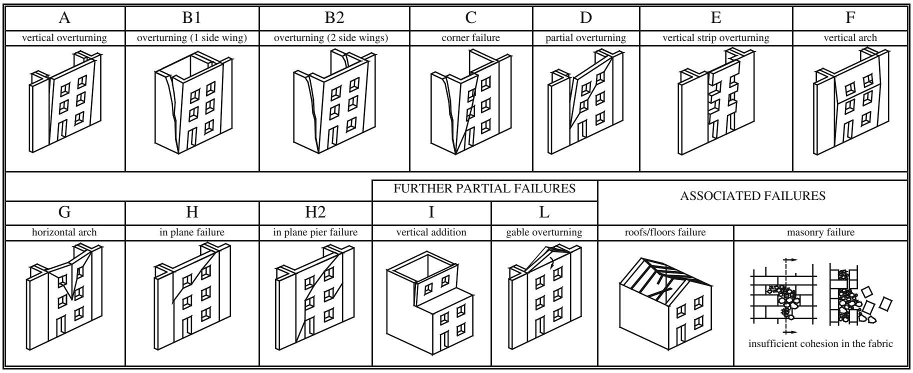


Fig. 11 Sketches corresponding to FaMIVE mechanisms: out-of-plane and in-plane mechanisms, partial failures and associated failures (D'Ayala and Speranza 2002, 2003; D'Ayala and Novelli 2011)

side wing involving only a party wall, mechanism B1, or overturning with two side wings involving both party walls, mechanism B2), inducing, occasionally, a partial collapse of the roof.

Corner buildings can develop an out of plane mechanism C involving only the upper triangular wedge of both façades when the connections between orthogonal walls are good but the quality of the fabric favors the occurrence of diagonal cracks.

A vertical strip overturning of the façade (mechanism E) can occur when parallel vertical cracks cause the detachment of a façade strip, due to the different stiffness between openings and piers.

Some buildings have developped a vertical or horizontal arch mechanism, depending on the distribution of connecting elements in the façade and the edges. In the first case (mechanism F), the overturning has been prevented by the presence of ties at the roof level, producing a movement of the intermediate floors out of the façade plane. In the second case (mechanism G), the bowing of the long unrestrained façade has produced a vertical crack in the middle of its length.

When masonry walls are subjected to horizontal actions parallel to their plane or the orthogonal walls are properly connected, local failure can happen, causing horizontal, vertical or diagonal cracks, developing in-plane mechanisms H or H2 (Fig. 12b). For these mechanisms, the crack pattern varies from hair-line to large and extensive cracks either in piers, in spandrels or in both, depending on the stress distribution within the masonry wall, the typology and quality of the masonry fabric, the geometry of the wall, the distribution and size of the openings, the support conditions, the connection efficiency between walls and floors and the level of maintenance.

In addition to out-of-plane and in-plane collapse mechanisms, other associate failures have been documented (Fig. 12c): total or partial failure of roofs and floors, partial failure of cornices and roof overhangs and, finally, masonry failure.

Out-of-plane collapse mechanisms involve, sometimes, roofs and floors, causing their total or partial failure, due to the out of plane movement of the façades. This effect is increased when horizontal structures and walls are poorly connected or when the wooden elements are badly preserved. One of the most extended damage in the area is the partial failure of cornices and roof overhangs, showing their inadequacy in seismic regions and the poor effectiveness of the stone corbels or iron brackets designed to improve their behaviour. The ocurrence of localized masonry failure in some buildings is due mainly to the poor quality and irregularity

(a) Out-of-plane mechanisms

Mechanism A: Vertical overturning of the façade due to poor or non-existent connection at edges or due to pounding effects:

Mechanism B1/B2: Overturning with 1/2 side wings:

Mechanism C: Corner failure

Mechanism D: Partial overturning

Mechanism E: Vertical strip overturning

Mechanism G: Horizontal arch mechanism

Mechanism F: Vertical arch mecanism

(b) In-plane mechanisms

In-plane mechanisms with variable crack pattern: Horizontal, diagonal and vertical cracks in spandrels and/or piers

(c) Associated failures

Total or partial failure of roofs and floors

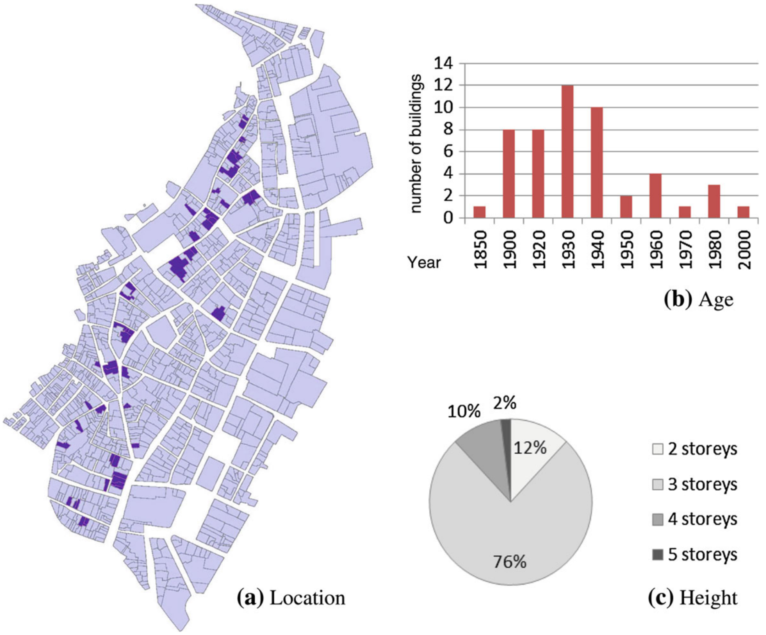
Partial failure of cornices and roof overhangs

Masonry failure

Fig. 12 Collapse mechanisms observed in the surveyed area: **a** out-of-plane mechanisms, **b** in-plane mechanisms and **c** associated failures

of the rubble stones, the insufficient bond between stones and mortar, the lack of transversal compactness and the deficient connections between the different wall leafs.

Although the number of observed out of plane mechanisms and total collapses of roofs and floors was low, the majority of the masonry residential buildings suffered slight to moderate non-structural damage and repairable structural damage in façades, internal walls, roofs and



(a) Location **(b)** Age **(c)** Height

Fig. 13 **a** Location, **b** age (buildings from 1980 to 2000 correspond to masonry buildings in which horizontal timber structures have been replaced with RC floors) and **c** heigth of the sample façades

cornices. There haven't been any total collapses during the earthquake in the surveyed area however, in the following months, some buildings have been demolished, mainly those which were abandoned or badly maintained before the event.

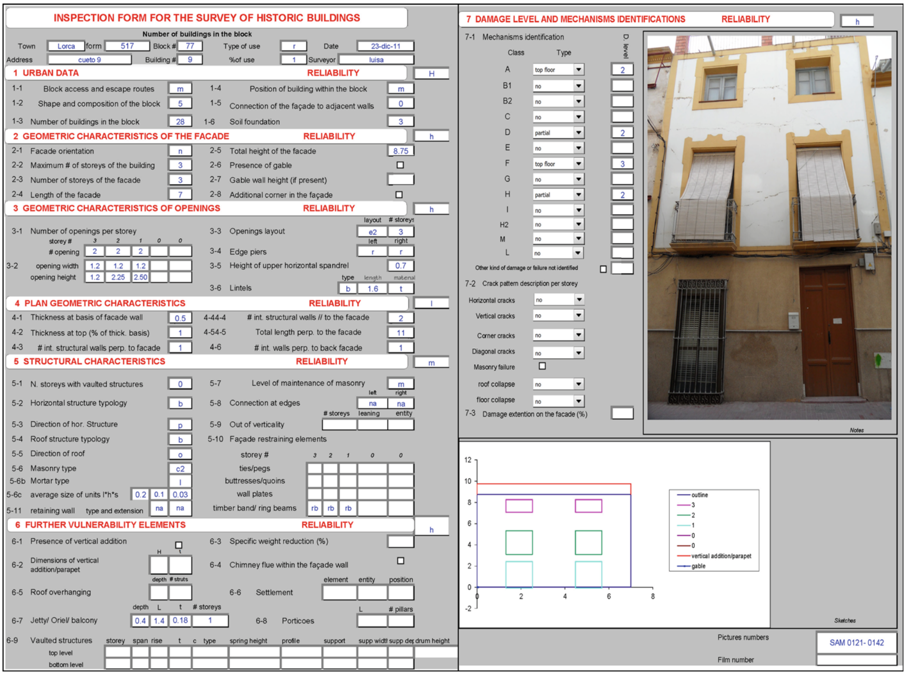
4 Damage level and collapse mechanism assessment

4.1 Sample description and data collection

After an initial on-site general survey on structural aspects, construction techniques, damage level and collapse mechanisms of unreinforced masonry residential buildings within the whole target area (Sect. 3), a sample of 65 façades corresponding to 50 residential buildings was selected and analysed.

Only URM residential buildings with masonry load bearing walls have been included in the sample: buildings with a concrete frame and original masonry façades without structural function and buildings completely rebuilt with a concrete structure have been neglected. Ruined buildings before the earthquake have also been excluded, due to the impossibility of establishing clearly the damages produced by the earthquake. On the other hand, 64 % of the selected buildings have a local statutory level of protection; a higher percentage than the 32 % corresponding to the whole area covered by the PEPRI, because protection commonly affects masonry buildings.

The location of surveyed buildings in the target area, their age (78 % built before 1940) and the number of storeys are shown in Fig. 13. Although most of the buildings have three storeys, differences up to two storeys are present, with considerable variation across the sample, in floor to floor height, plan shape, street front's dimensions, opening layouts, etc.



INSPECTION FORM FOR THE SURVEY OF HISTORIC BUILDINGS

Number of buildings in the block

Town: Lorca form: 517 Block #: 77 Type of use: r Date: 23-dic-11
Address: cueto 9 Building #: 9 %of use: 1 Surveyor: luisa

1 URBAN DATA RELIABILITY: H

1-1 Block access and escape routes: m
1-2 Shape and composition of the block: 5
1-3 Number of buildings in the block: 28
1-4 Position of building within the block: m
1-5 Connection of the façade to adjacent walls: 0
1-6 Soil foundation: 3

2 GEOMETRIC CHARACTERISTICS OF THE FACADE RELIABILITY: h

2-1 Facade orientation: n
2-2 Maximum # of storeys of the building: 3
2-3 Number of storeys of the facade: 3
2-4 Length of the facade: 7
2-5 Total height of the facade: 8.75
2-6 Presence of gable ☐
2-7 Gable wall height (if present):
2-8 Additional corner in the façade ☐

3 GEOMETRIC CHARACTERISTICS OF OPENINGS RELIABILITY: h

3-1 Number of openings per storey

storey #	3	2	1	0	0
# opening	2	2	2		
3-2 opening width	1.2	1.2	1.2		
opening height	1.2	2.25	2.50		

3-3 Openings layout: layout e2, # storeys 3
3-4 Edge piers: left r, right r
3-5 Height of upper horizontal spandrel: 0.7
3-6 Lintels: type b, length 1.6, material t

4 PLAN GEOMETRIC CHARACTERISTICS RELIABILITY: l

4-1 Thickness at basis of facade wall: 0.5
4-2 Thickness at top (% of thick. basis): 1
4-3 # int. structural walls perp. to facade: 1
4-44-4 # int. structural walls // to the facade: 2
4-54-5 Total length perp. to the facade: 11
4-6 # int. walls perp. to back facade: 1

5 STRUCTURAL CHARACTERISTICS RELIABILITY: m

5-1 N. storeys with vaulted structures: 0
5-2 Horizontal structure typology: b
5-3 Direction of hor. Structure: p
5-4 Roof structure typology: b
5-5 Direction of roof: o
5-6 Masonry type: c2
5-6b Mortar type: l
5-6c average size of units l*h*s: 0.2 0.1 0.03
5-11 retaining wall type and extension: na na
5-7 Level of maintenance of masonry: m
5-8 Connection at edges: left na, right na
5-9 Out of verticality: # storeys, leaning, entity:
5-10 Façade restraining elements

storey #	3	2	1	0	0
ties/pegs					
buttresses/quoins					
wall plates					
timber band/ ring beams	rb	rb	rb		

6 FURTHER VULNERABILITY ELEMENTS RELIABILITY: h

6-1 Presence of vertical addition ☐
6-2 Dimensions of vertical addition/parapet: H, t:
6-3 Specific weight reduction (%):
6-4 Chimney flue within the façade wall ☐
6-5 Roof overhanging: depth, # struts:
6-6 Settlement: element, entity, position:
6-7 Jetty/ Oriel/ balcony: depth 0.4, L 1.4, t 0.18, # storeys 1
6-8 Porticoes: L, # pillars:
6-9 Vaulted structures

	storey	span	rise	t	c	type	spring height	profile	support	supp widt	supp de	drum height
top level												
bottom level												

7 DAMAGE LEVEL AND MECHANISMS IDENTIFICATIONS RELIABILITY: h

7-1 Mechanisms identification

Class	Type	D. level
A	top floor	2
B1	no	
B2	no	
C	no	
D	partial	2
E	no	
F	top floor	3
G	no	
H	partial	2
I	no	
H2	no	
M	no	
L	no	
Other kind of damage or failure not identified ☐		

7-2 Crack pattern description per storey

Horizontal cracks	no
Vertical cracks	no
Corner cracks	no
Diagonal cracks	no
Masonry failure	☐
roof collapse	no
floor collapse	no

7-3 Damage extention on the facade (%):

Notes

Sketches

Pictures numbers: SAM 0121- 0142
Film number:

Fig. 14 Famive electronic inspection form (D'Ayala and Novelli 2011). Example of a surveyed façade in Lorca

A detailed inspection of the sample building façades was carried out. Focusing on the definition of all the parameters influencing the seismic performance of masonry buildings, a systematic collection of data from each façade was acquired (mostly from the outside), recording the following information in the FaMIVE electronic inspection form (Fig. 14):

- block and building identification
- block characteristics (shape, number of buildings)
- position of the building within the block
- geometric characteristics of the façade (orientation, number of storeys, height, length, thickness and verticality)
- openings characteristics (layout, number, size and spacing)
- position and number of the internal walls
- construction and structural details
- floors and roof structures characteristics (typology, orientation)
- identification of the masonry units: material (rubble, dressed stone, brickwork), dimensions, overlap, quality and level of maintenance
- strengthening elements (ties, ring beams, quoins)
- vulnerability elements (oriels, jetties, roof overhanging)
- crack pattern description
- identification of the collapse mechanisms and damage level
- reliability of the collected information

All these data are essential for the assessment of the most likely collapse mechanisms to occur, the associated level of damage and the seismic vulnerability. The street survey was

Table 3 Position of the surveyed buildings within the block in percentage

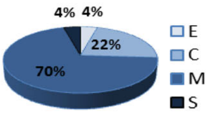
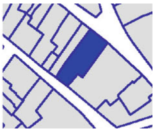
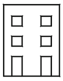
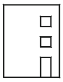
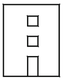
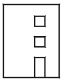
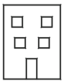
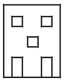
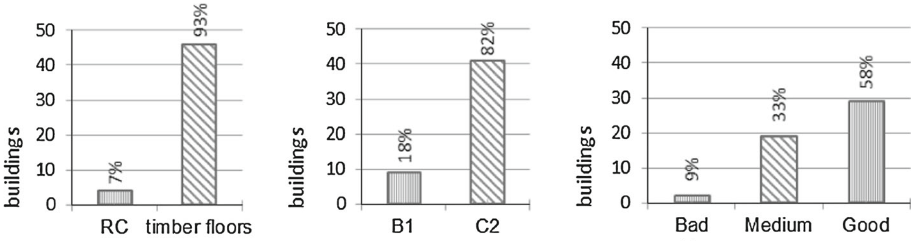
Position of the analysed buildings within the block	End of block building (**E**)	Corner building (**C**)	Intermediate building -1 wall free- (**M**)	Intermediate building -2 walls free- (**S**)
				

Table 4 FaMIVE opening layout classification (D'Ayala and Novelli 2011)

(E2)	(E1)	(CV)	(LV)	(v)	(X)	others
						
83%	3%	6%	3%	0%	4%	1%

Sample percentages



(a) Horizontal structure typology **(b)** Masonry fabric typology **(c)** Level of maintenance

Fig. 15 Sample characteristics in percentages: **a** Horizontal structure typology (RC: RC floors and timber floors: traditional timber beams and joists with lightweight vaults floors), **b** masonry fabric typology (B1: kiln brickwork and C2: poor quality rubble stone, according to FaMIVE description) and **c** level of maintenance (bad, medium and good)

completed including photographic documentation, measured drawings and, when possible, more detailed information taken from the inside of the buildings.

The position of the buildings within the block and the opening layout are factors which influence the type of collapse mechanism to be developed. FaMIVE code for both parameters and their respective percentages in the analyzed sample are represented in Tables 3 and 4.

The bearing system is composed by sets of walls parallel to the main façade, with, depending on the building plan, some interior orthogonal ones, additional to the party walls. Floors and roofs are oriented either parallel or perpendicular to the facades, being the second option the best position to stabilize the façade walls providing out of plane stiffness.

Sample characteristics regarding horizontal structure typology, masonry fabric typology and level of maintenance in percentages are shown in Fig. 15. The percentage of façades with bad level of maintenance is very low because, according to the selection criteria mentioned in this section, ruined buildings have not been included in the sample.

All the façades have balconies (58.3 % at one storey, 40 % at two storeys and only 1.7 % at three storeys), although their depth is, generally, less than 0.4 m, resulting in a relatively small associated overturning moment.

On the other hand, the survey revealed that 58 % of the façades are well connected at one or both edges, being an extended practice the use of ring beams or timber bands (81 %), although, despite of being in a seismic-prone area with a history of previous destructive earthquakes, only a few restraining elements like iron ties (17 %) linking the façades to the floors or the party walls were recorded, while dressed stone quoins, providing efficient connection among orthogonal walls, are more common (23 %).

4.2 Discussion of results: correlation between observed and calculated collapse mechanisms and level of damage

Although validated with empirical data from various earthquakes, a correlation between observed and calculated collapse mechanisms and damage levels is necessary to establish the accuracy of the numerical values assigned to FaMIVE parameters with the specific construction characteristics of the building stock in the area and to determine the need for implementing new masonry fabric elements or connection systems in the form.

During the field survey the authors have associated to each façade's crack pattern a representative mechanism among the possible ones (in some cases up to three), being sometimes difficult to identify which is the prevalent, especially for the low and moderate damaged buildings. The observed mechanisms are mapped in Fig. 16a. In-plane mechanisms, H or H2, have the greatest occurrence (67 %), distantly followed by three out-of-plane mechanisms: partial overturning, D (9 %), overturning with 1 side wing, B1 (6 %) and vertical strip overturning, E (6 %).

Taking into account the gathered information of each façade, FaMIVE identifies all the feasible mechanisms, selecting the prevalent one, depending on the collapse load factor and the damage extent, classifying the building into four vulnerability classes (low, medium, high and extreme). It is worth pointing out that, sometimes, this first choice is not the mechanism that might really occur. FaMIVE predicted mechanisms are mapped in Fig. 16b. FaMIVE has estimated that the majority of the sample buildings will, also, develop an in-plane mechanism, mainly H2, although with a low percentage (40 %). Other representative predicted mechanisms are the vertical overturning of the façade, A (32 %) and the partial overturning, D (20 %).

The correlation has been established not only between the observed mechanism and the first FaMIVE proposed mechanism but also with the second FaMIVE choice: 44 % of the observed mechanisms are predicted as the prevalent ones, while 42 % correspond to the second choice. Not matching prediction represents only 14 % (Fig. 16c).

The main difference is that the percentage for observed out-of-plane mechanisms (33 %) is lower than the corresponding percentage for the predicted ones (60 %). As has been proved in previous studies about the seismic performance of similar masonry buildings, when façades are prevented from overturning by efficient connections between orthogonal walls, the most probable collapse mechanisms would be the in-plane ones, however, the façade will fail with an out-of-plane mechanism when there is lack of connection. During the survey, it has been very difficult to establish in some buildings the presence of internal strengthening devices and their efficiency. In absence of accurate information, this uncertainty has been taking into account considering that the walls were poorly connected and assigning a low level of reliability in FaMIVE inspection form. Therefore, differences in the collapse mechanism prediction can be explained by the unnoticed presence of restraining elements that are preventing the occurrence of out-of-plane mechanisms.

Regarding the relationship between vulnerability classes and damage level, FaMIVE predicts a more vulnerable damage scenario (see percentages of damage degrees and vul-

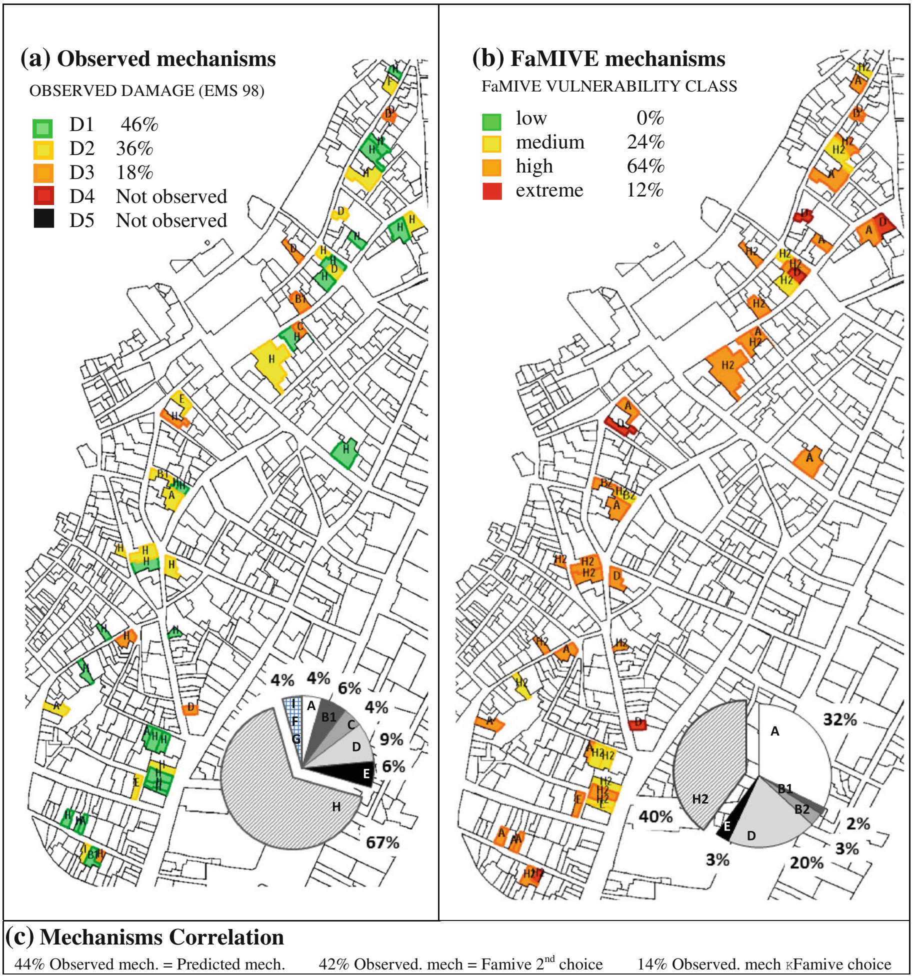


Fig. 16 **a** Observed collapse mechanisms and damage levels, **b** FaMIVE predicted collapse mechanisms and vulnerability classes and **c** mechanisms correlation

nerability classes in Fig. 16a, b), which might be considered a relatively good correlation, considering the uncertainties concerning the surveyed data.

To explain better the differences between FaMIVE predictions and surveyed damage, a comparison has been made depending on the horizontal structure and the masonry fabric typologies (Fig. 17), showing that differences correspond to rubble masonry walls with timber floors (out-of-plane mechanisms: 30 % observed, 54 % predicted and in-plane mechanisms: 50 % observed, 26 % predicted).

Quality, dimensions and construction characteristics of masonry fabric are relevant factors in seismic performance, being rubble masonry walls the most difficult to characterize. The average size of rubble walls units and overlap data have been obtained directly from open cracks in the façades or from demolished nearby buildings or party walls. On the other hand, despite the fact that observed walls were neither uniform nor homogeneous, the same unit sizes and overlap have been considered for all rubble façades.

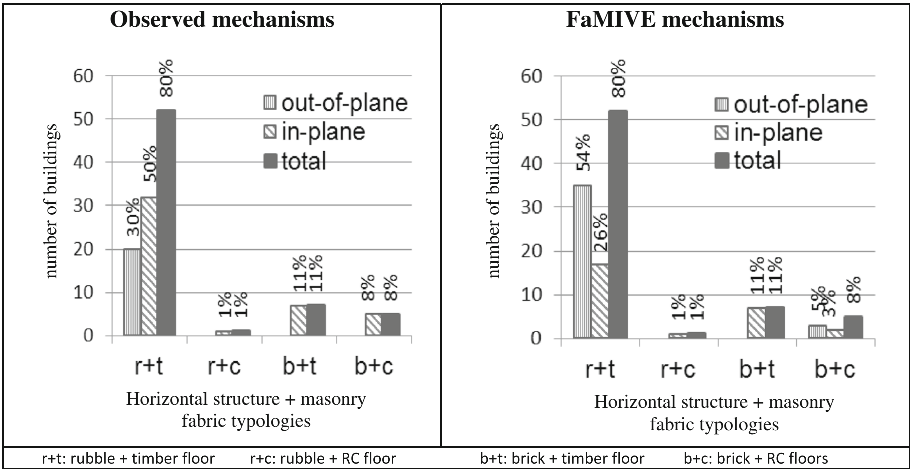


Fig. 17 Observed and calculated mechanisms depending on horizontal structure and masonry fabric typologies

High reliability and availability of accurate data regarding masonry characteristics is crucial for the collapse mechanism and final vulnerability assessment, due to their influence on the results. An improvement in rubble characteristics in some of the sample walls would likely change the predicted mechanism from out-of-plane to in-plane and reduce their vulnerability. From this point of view differences between observed and predicted mechanisms are justified, taking into account that it has not been possible to get accurate information for each analysed façade. This low reliability has influenced and increased the differences between predicted and observed scenarios.

Observed or predicted partial or total failure of the roofs and floors are mapped in Fig. 18a, b, respectively. Regarding FaMIVE the percentage of horizontal structures involved in a partial or total failure is clearly higher than the percentage of the observed collapses. As the survey has been generally carried out from the exterior (either for security reasons or due to the absence of inhabitants), data reliability in this specific subject is the lowest one. Therefore the percentage of real collapses might be possibly higher.

Taking into account the particularities of the masonry building stock in the area, the main factors influencing the in-plane and out-of-plane seismic behaviour have been:

- construction techniques (good organization, regularity and verticality of bearing walls, presence of internal load bearing walls perpendicular to the facade, wall thickness, floor and roofs typologies, presence of strengthening devices or connections between different walls and floor structures),
- geometrical configuration (number of storeys, dimension, position and spacing of openings),
- mechanical quality of the masonry fabric (type of elements, mortar quality, overlap, good connections),
- state of preservation and other common elements governing vulnerability like building position within the block, slenderness, presence of coupling or pounding effects or ulterior alterations and interventions.

A proper maintenance of façades and roofs might avoid building decay resulting in a better seismic performance in accordance with their expected strength, preventing water infiltration and ensuring preservation of wooden elements and strengthening devices conditions.

Fig. 18 Observed and predicted roofs and floors failures

5 Conclusions

In order to study the seismic response of unreinforced masonry buildings in Lorca's historic centre after 11th May 2011 earthquake, an on-site survey campaign on a sample of buildings within the area covered by the PEPRI was carried out, consisting in an in-situ data collection, level of damage description and collapse mechanisms identification. A total number of 65 façades from 50 unreinforced masonry residential buildings were evaluated, most of them dating from the first half of the twentieth century, 93 % with timber floors (timber beams and joists with lightweight vaults) and only 7 % with RC floors (RC beams and joists with ceramic vaults), being roofs made of timber beams and joists with a traditional covering made out of a reed and plaster deck or a brick deck under ceramic curved tiles.

The survey showed that ordinary residential masonry buildings suffered low to moderate non-structural damage consisting mainly in slight in-plane cracks, partial failures of cornices and roof overhangs, repairable structural damage in façades or internal walls and a small number of partial failures of roofs and floors. Most of the buildings showed a damage grade 1 or 2 (46 and 36 %, respectively), revealing a good behaviour, in general terms. Having checked the state of the analysed buildings before the earthquake with Google Street View, it must be highlighted that a significant number of listed masonry residential buildings were previously abandoned and showed a bad level of maintenance in roofs and façades, being the most damaged after the earthquake. There have not been total collapses during the earthquake in the surveyed area, however, in the following months, some buildings have been demolished, mainly those which were abandoned or badly maintained before the event.

A simultaneous analysis has been conducted with FaMIVE method. Results have been compared with the observed collapse mechanisms, showing a fair correlation: 86 % of the FaMIVE predicted collapse mechanisms as first or second choice match the observed ones. Regarding the final vulnerability assessment, FaMIVE predicted worse damage scenarios, as expected, taking into account that FaMIVE procedure chooses the "worst" mechanism in terms of the collapse load factor and the damage extent, and when for two or more mechanisms the load factor and damage extent have similar values, FaMIVE selects the one with the most damaging consequences which might not be the one in reality. These differences have been enlarged considering the data collection process, not only because the reliability of some important information such as masonry characteristics (quality, size of units, overlap) or the presence of strengthening elements was low, but also because a street survey cannot take into account the internal damages. Despite of this fact, when surveyed data were sufficiently reliable, good accordance was found in terms of both predicted collapse mechanisms and levels of damage, showing the accuracy of the numerical values assigned to FaMIVE parameters with the specific construction characteristics of URM buildings in Lorca city centre.

Effective connections between façades and party walls, a good maintenance level of masonry and roofs and the use of specific reinforcement elements have proved to be relevant factors in lowering the vulnerability and improving the seismic behaviour of unreinforced masonry structures in Lorca historic centre. Repair and replacement of decayed masonry should be one of the first treatments for all the buildings in the sample, followed by a study of the most suitable strengthening strategies to reduce the seismic risk, considering the historical value of the building stock.

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References

Basset-Salom L, Guardiola-Víllora A (2013) Influence of the maintenance in seismic response of Lorca historic centre masonry residential buildings after 11 May Earthquake. Studies, Repairs and Maintenance of Heritage Architecture XIII. WIT Trans Built Environ 131:343–354. http://library.witpress.com

Benito B, Murphy P, Tsige M, Martínez-Díaz JJ, Gaspar-Escribano JM, García-Mayordomo J, Jiménez ME, García MJ, Canora C, Álvarez-Gómez JA, García-Flores I (2006) Riesgo Sísmico de la Comunidad Autónoma de la Región de Murcia (Proyecto RISMUR). Volumen 6: Informe final. Instituto Geográfico Nacional y Dirección General de Protección Civil Región de Murcia

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

Buforn E, Benito B, Sanz de Galdeano C, del Fresno C, Muñoz D, Rodríguez I (2005) Study of the damaging earthquakes of 1911, 1999 and 2002 in risk implications. Bull. Seismol. Soc. Am. 95:549–567

Cabañas L, Carreño E, Izquierdo A, Martínez JM, Capote R, Martínez J, Benito B, Gaspar J, Rivas A, García J, Pérez R, Rodríguez MA, Murphy P (2011) Informe del sismo de Lorca del 11 de mayo de 2011. IGN, UCM, UPM, IGME, AEIS. http://www.ign.es/ign/resources/sismologia/www/lorca/Lorcainfo2011.pdf. Accessed 15 Dec 2011

Catalogue of Protected Buildings (1994) Departamento de Urbanismo de Lorca. http://www.urbanismo.lorca.es/generar/cgi-bin/mapserv.exe. Accessed 15 Dec 2011

Carocci CF, Lagomarsino S (2009) Gli edifici in muratura nei centri storici dell' Aquilano. Progettazione Sismica no 3, pp 117–134

D'Ayala DF (2003) Seismic vulnerability and strengthening of historic building, in Fener and Balat Districts, Istanbul EU-Fatih Municipality Programme: Rehabilitation of Fener and Balat Districts DELTUR/MEDTQ/53-02 [PDF]. http://www.fenerbalat.org/admin/files/250_DDayalaReport.pdf. Accessed 13 Jan 2012

D'Ayala DF (2005) Force and displacement based vulnerability assessment for traditional buildings. Bull Earthq Eng 3(3):235–265

D'Ayala DF (2006) Proceedings of the getty seismic Adobe Project 2006 colloquium seismic vulnerability and conservation strategies for Lalitpur minor, Heritage, pp 120–134

D'Ayala DF, Ansal A (2009) Non-linear push over assessment of historic buildings in Istanbul to define vulnerability functions. In: WCCE-ECCE-TCCE joint conference: earthquake and Tsunami, Istanbul, Turkey, p 128

D'Ayala DF, Novelli V (2011) Inspection form for the survey of historic buildings, Instructor Manual (WP6. Models for the seismic Vulnerability assessment at territorial scale). EU-FP7 (2010–2012). Performance based approach to the earthquake protection of cultural heritage in European and Mediterranean countries (PERPETUATE). www.perpetuate.eu

D'Ayala DF, Paganoni S (2011) Assessment and analysis of damage in L'Aquila historic city centre after 6th April 2009. Bull Earthq Eng 9:81–104

D'Ayala DF, Speranza E (2002) An integrated procedure for the assessment of seismic vulnerability of historic buildings. In: Proceedings of 12th European conference of earthquake engineering, Paper Reference 561. Elsevier Science Limited, London

D'Ayala DF, Speranza E (2003) Definition of collapse mechanisms and seismic vulnerability of historic masonry buildings. Earthq Spectra 19(3):479–509

Gaspar-Escribano JM, Benito B (2007) Ground motion characterization of low-to-moderate seismicity zones and implications for seismic design: lessons from recent, Mw∼4.8, damaging earthquakes in Southeast Spain. Bull Seismol Soc Am 97:531–544

Gaspar-Escribano JM, Murphy P, Benito B (2005) Study of ground motions and damage trends in different building types caused by recent low-magnitude earthquakes in SE Spain. Lessons for defining seismic design criteria. In: Proceedings 250th anniversary of the 1755 Lisbon earthquake, Lisbon, 1–4 November 2005

Gaspar-Escribano JM, Benito B, García-Mayordomo J (2008) Hazard-consistent response spectra in the Region of Murcia (Southeast Spain): comparison to earthquake-resistant provisions. Bull Earthq Eng 6:179–196

Goula X, Irizarry J, Figueras S, Macau A, Barbat A, Carreño LM, Lantada N, Valcarcel J (2011) El terremoto de Lorca del 11 de Mayo de 2011. Informe de la inspección y de los trabajos de campo realizados, Monografies técniques, Barcelona, IGC

Grünthal G (1998) European Macroseismic Scale 1998. In: Cahiers du Centre Européen de Géodynamique et de Séismologie, Luxembourg, 99p

Guardiola-Víllora A, Basset-Salom L (2012) Risk of protecting residential buildings in seismic historic centres. Lorca (Spain) Experience after 11th May 2011 Earthquake. In: Proceedings of the ICOMOS ICORP international symposium on cultural heritage protection in times of risk: challenges and opportunities, Istambul. Yildiz Technical University Press

IGN (2011) Instituto Geográfico Nacional. Ministerio de Fomento. Serie terremoto NE Lorca (Murcia). 11 de mayo 2011. www.fomento.gob.es/NR/rdonlyres/4196D838-3EB6.../Lorca.pdf. Accessed 15 Dec 2011

IGN (2012) Instituto Geográfico Nacional. Ministerio de Fomento. http://www.fomento.gob.es/mfom/lang_castellano/direcciones_generales/instituto_geografico/geofisica/sismologia/. Accessed 15 Dec 2011

Lorca's City Council (2000) (Ayuntamiento de Lorca). Plan Especial de protección y rehabilitación integral en el conjunto histórico artístico de Lorca (PEPRI. Departamento de Urbanismo de Lorca. http://www.urbanismo.lorca.es/PEPRI.asp. Accessed 15 Dec 2011

Lorca's City Council (2011) (Ayuntamiento de Lorca). Visor geográfico seísmo de Lorca. http://www.lorca.es/ficheros/file/sitLorcaSeismo/index.asp. Accessed 10 June 2011

Martínez-Solares JM, Mezcua-Rodriguez J (2002) Catálogo sísmico de la Península Ibérica (880 a.C.-1900). Monografías no 18. Instituto Geográfico Nacional. Madrid. www.ign.es/ign/resources/sismologia/.../Catalogohasta1900.pdf. Accessed 21 Oct 2012

Muñoz-Clares M, Fernandez-Carrascosa M, Alcolea-López MO, Arcas-Navarro MC, Arcas-Ruiz N, Caro-del-Vas P, Cruz-López MT, Garcia-Poveda M, Garcia-Valera MA, Llamas-Martinez B, Ruiz-Llanes AE (2012) Sismicidad histórica y documentación municipal: el caso de Lorca. Boletín Geológico y Minero 123(4):415–429

Murphy P (1999) Earthquake in the River Mula region, February 2 1999. Study of damage to buildings. Física de la Tierra 11:253–267

Murphy P (2006) La Vulnerabilidad de la Edificación de la Región de Murcia, en Riesgo Sísmico de la Comunidad Autónoma de la Región de Murcia (Proyecto RISMUR). Volumen 3: Vulnerabilidad sísmica. Instituto Geográfico Nacional y Dirección General de Protección Civil Región de Murcia