

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 $M_w=5.1$ 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 2002, 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.

KEYWORDS: masonry structures, seismic vulnerability, damage assessment, Lorca historic centre, collapse mechanisms, FaMIVE.

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 b.C. (Martinez-Solares and Mezcuca-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

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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.

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 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 $M_w=4.5$ foreshock at 15:05:13 (lat: 37041 N, long: 16812 W) and six tremors including a $M_w = 2.6$, the $M_w=5.1$ 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 (figure 2), including a $M_w = 3.9$ and a $M_w = 2.9$ (IGN 2011).

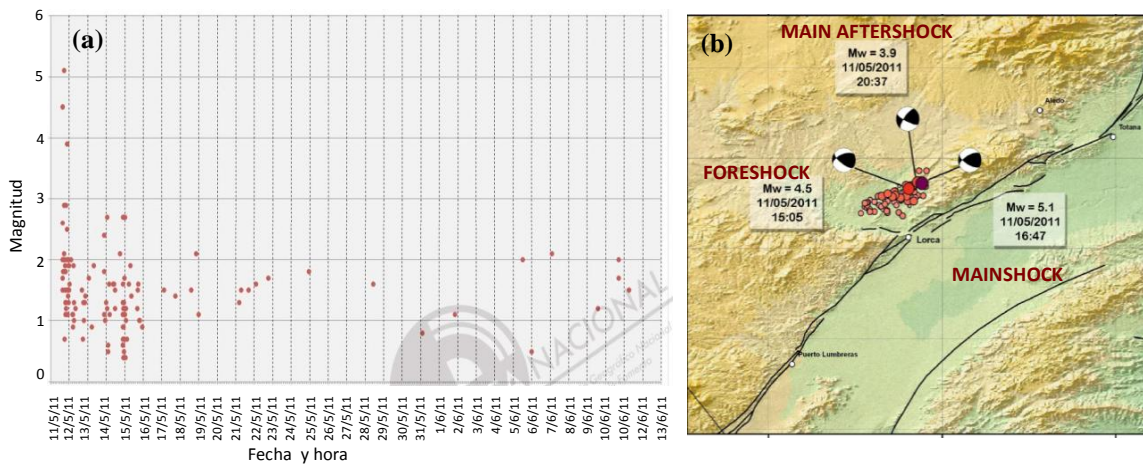


Fig. 2 a) Earthquake sequence (IGN 2011) and **b)** location of the foreshock, mainshock and main aftershock (Cabañas et al. 2011)

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 0.29g and 0.37g, 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 km and 3 km to Lorca seismic station) and to the surface (2 km 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 two hundred years.

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 to 4 storeys for URM buildings and 5 to 6 for RC buildings) are shown in figures 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 braced façades, (e) abandoned buildings waiting to be declared ruined and (f) new reinforced concrete buildings built from 1970 to 2000 (see figure 5).



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

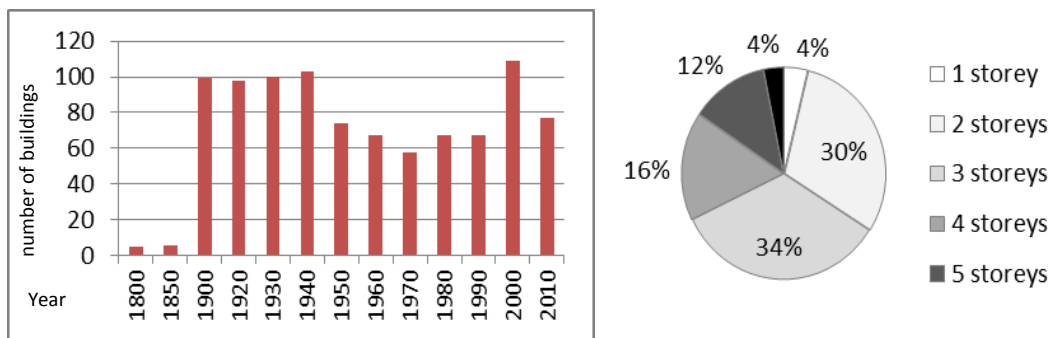


Fig. 4 Building ages (cadastral database 2011) and number of storeys

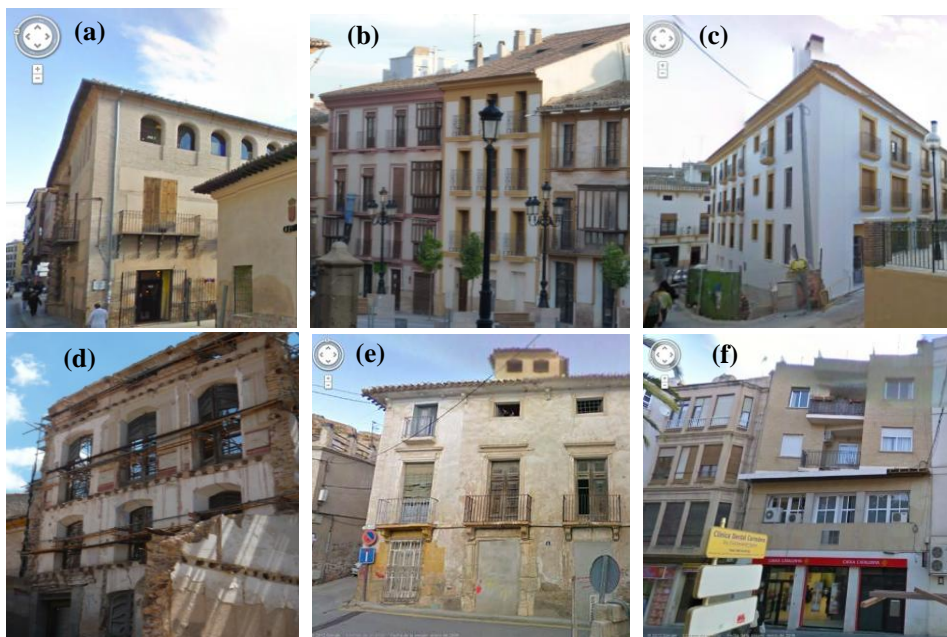


Fig. 5 Buildings in the surveyed area, before the earthquake: **a)** fullrestored mansions with residential or administrative use, **b)** traditional residential buildings, **c)** new apartment dwellings, **d)** cleaned up buildings, **e)** abandoned buildings and **f)** new reinforced concrete buildings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

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 (figure 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 cm to 80 cm having, sometimes, significant windows and balconies; whereas the thickness of the walls between adjacent buildings ranges from 20 cm 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 XIX century, increasing the height from one or two up to four storeys (Murphy 2006). Typical size of bricks is 20x10 x3/4 cm (before 1950) or 24x12x4/5 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 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 (figure 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 (figure 8). In these situations attention has been paid to possible coupling effects, considering buildings together instead of individually.

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.



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

Table 1 Masonry fabric typologies in the surveyed area







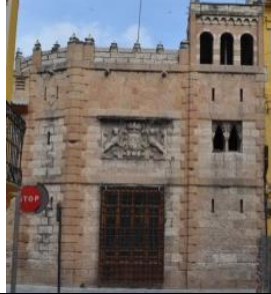

Residential Buildings			
			
Rubble masonry fabric		Brick masonry fabric	
Monumental Buildings and Mansions			
			
Brick and rubble masonry fabric		Stone masonry fabric	



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

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 (figure 9).

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.



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

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

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

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 (figure 10). Mechanisms were classified using the updated catalogue of mechanisms (see sketches in figure 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 section 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.

a) Classification of damage to masonry buildings	b) Buildings in the area
	
	
	
	
	<p data-bbox="1118 1951 1262 1977">Not observed</p>

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

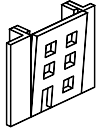
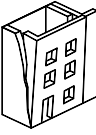


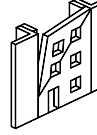
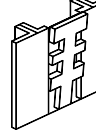

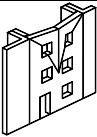
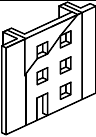
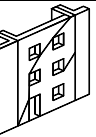
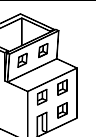
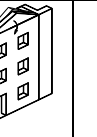

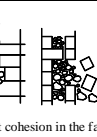
A	B1	B2	C	D	E	F
vertical overturning	overturning (1 side wing)	overturning (2 side wings)	corner failure	partial overturning	vertical strip overturning	vertical arch
						
			FURTHER PARTIAL FAILURES		ASSOCIATED FAILURES	
G	H	H2	I	L		
horizontal arch	in plane failure	in plane pier failure	vertical addition	gable overturning	roofs/floors failure	masonry failure
						

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)

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

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.

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 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 developed 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 (figure 12 b). 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 (figure 12 c): total or partial failure of roofs and floors, partial failure of cornices and roof overhangs and, finally, masonry failure.

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 mechanism
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

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 occurrence of localized masonry failure in some buildings is due mainly to the poor quality and irregularity of the rubble stones, the insufficient bond between stones and mortar, the lack of transversal compactness and the deficient connections between the different wall leaves.

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 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

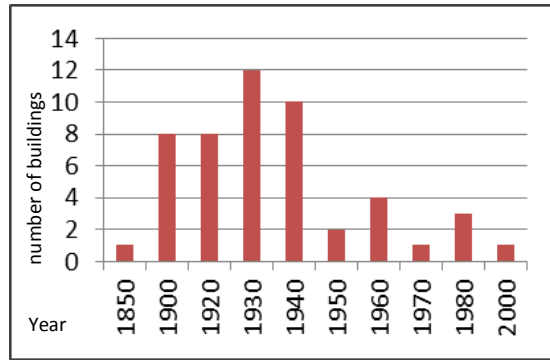
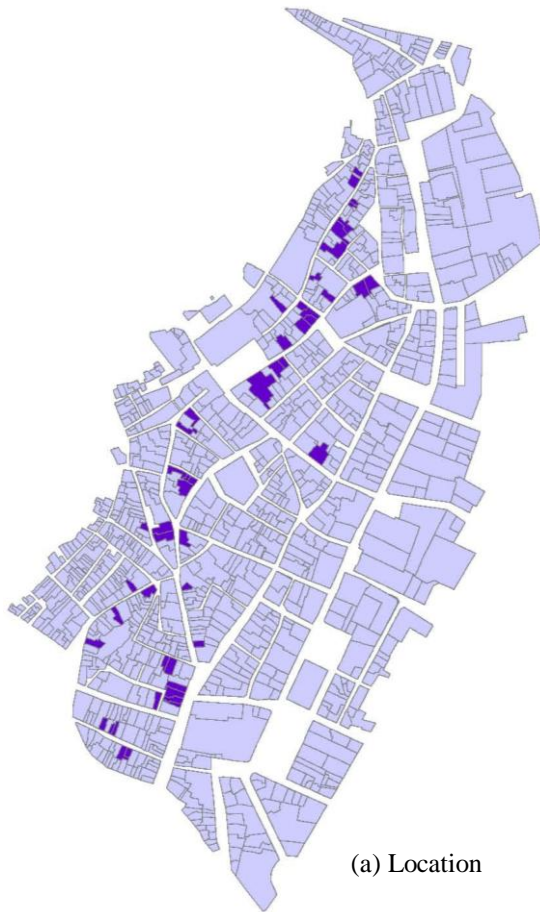
After an initial on-site general survey on structural aspects, construction techniques, damage level and collapse mechanisms of unreinforced masonry residential buildings within the whole target area (section 3), a sample of 65 façades corresponding to 50 residential buildings was selected and analysed.

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.

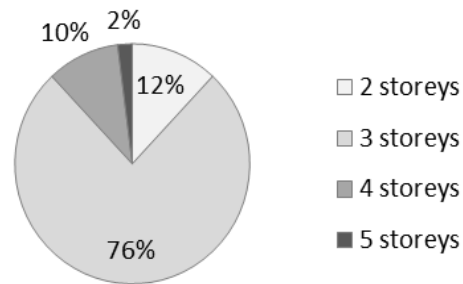
The location of surveyed buildings in the target area, their age (78% built before 1940) and the number of storeys are shown in figure 13. Although most of the buildings have three storeys, differences up to two storeys are present, with considerable variation across the sample, in floor to floor height,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

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 (figure 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



(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) height of the sample façades

INSPECTION FORM FOR THE SURVEY OF HISTORIC BUILDINGS

Town: Lorca Form: 517 Block #: 77 Type of use: r Date: 23-dic-11
 Address: c/tao 9 Building #: 9 %of use: 1 Surveyor: luisa

1 URBAN DATA RELIABILITY: H

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

2 GEOMETRIC CHARACTERISTICS OF THE FACADE RELIABILITY: h

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

3 GEOMETRIC CHARACTERISTICS OF OPENINGS RELIABILITY: h

3-1 Number of openings per storey: layout # storeys
 # opening: 2 2 2 2 ac 3
 3-2 opening width: 1.2 1.2 1.2 3-4 Edge piers: r r r
 opening height: 1.2 2.35 2.50 3-5 Height of upper horizontal spandrel: 0.7
 3-6 Lintels: type length material
 b 1.6 t

4 PLAN GEOMETRIC CHARACTERISTICS RELIABILITY: i

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

5 STRUCTURAL CHARACTERISTICS RELIABILITY: m

5-1 N. storeys with vaulted structures: 0 5-7 Level of maintenance of masonry: m
 5-2 Horizontal structure typology: b 5-8 Connection at edges: na na
 5-3 Direction of hor. Structure: p 5-9 Out of verticality: leaning entity
 5-4 Roof structure typology: b 5-10 Façade restraining elements: storey # ties/pegs
 5-5 Direction of roof: a buttresses/quoins
 5-6 Masonry type: c2 wall plates
 5-6b Mortar type: 0
 5-6c average size of units (h's): 0.2 0.1 0.03 timber band/ ring beams: rb rb rb
 5-11 retaining wall: type and extension: na na

6 FURTHER VULNERABILITY ELEMENTS RELIABILITY: h

6-1 Presence of vertical addition: 6-3 Specific weight reduction (%):
 6-2 Dimensions of vertical addition/parapet: h t 6-4 Chimney flue within the façade wall:
 6-5 Roof overhanging: depth # storeys 6-6 Settlement: element entity position
 6-7 Jetty/ Oriel/ balcony: depth L t # storeys 6-8 Porticoes: L # pillars
 0.4 1.4 0.18 1
 6-9 Vaulted structures: storey span rise t c type spring height profile support supp. width supp. dia drum height
 top level: bottom level:

7 DAMAGE LEVEL AND MECHANISMS IDENTIFICATIONS RELIABILITY: h

7-1 Mechanisms identification

Class	Type	Severity
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 extension on the facade (%)

Picture numbers: SAM 0121-0142
 Film number:

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

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 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 table 3 and table 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 figure 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 0.4m, resulting in a relatively small associated overturning moment.

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

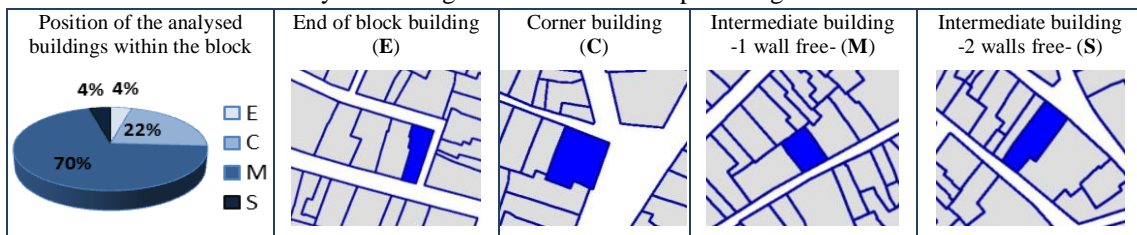


Table 4 FaMIVE opening layout classification (D'Ayala and Novelli 2011). Sample percentages

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

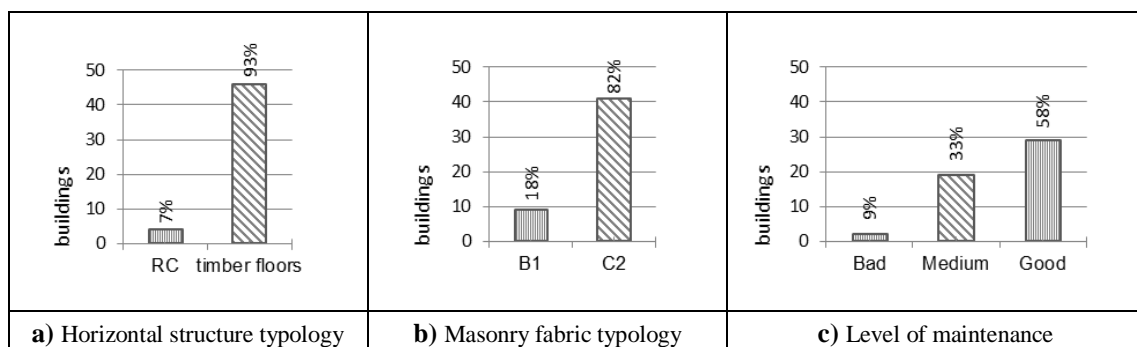


Fig. 15 Sample characteristics in percentages: **a)** Horizontal structure typology (RC: RC floors and timber floors: traditional timber beams and joists with lightweight vaults floors), **b)** masonry fabric typology (B1: kiln brickwork and C2: poor quality rubble stone, according to FaMIVE description)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

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 figure 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 figure 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% (figure 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.

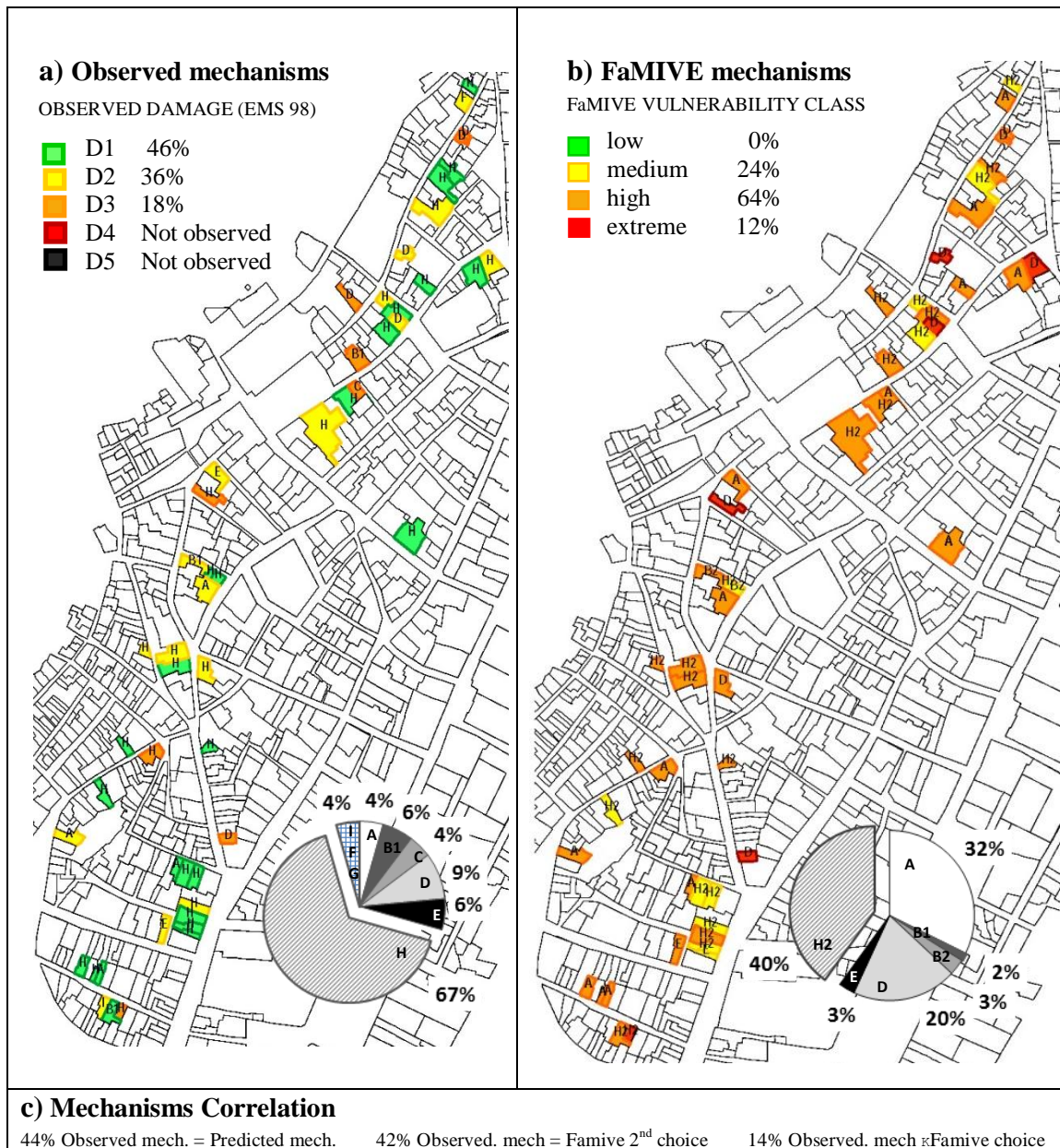


Fig. 16 a) Observed collapse mechanisms and damage levels, **b)** FaMIVE predicted collapse mechanisms and vulnerability classes and **c)** Mechanisms correlation

Regarding the relationship between vulnerability classes and damage level, FaMIVE predicts a more vulnerable damage scenario (see percentages of damage degrees and vulnerability classes in figure 16 a, 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 (figure 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.

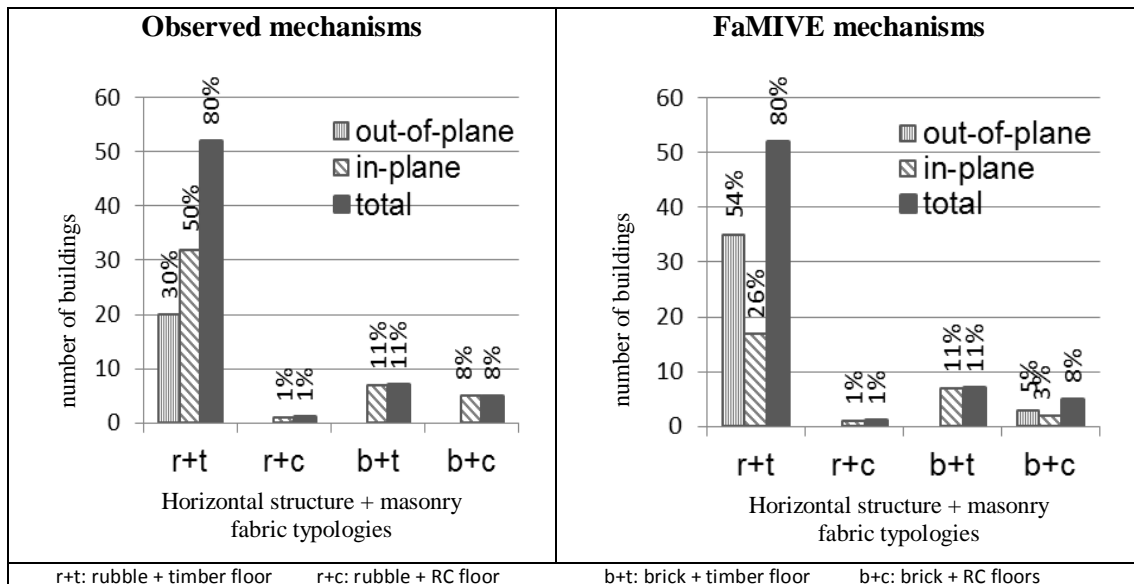


Fig. 17 Observed and calculated mechanisms depending on horizontal structure and masonry fabric typologies

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 figure 18a and 18b, 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 20th 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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