Performance of cultural heritage of Lorca (Spain) during the two small earthquakes of May 11th, 2011

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SUMMARY
Two small earthquakes took place on May 11th, 2011 (Mw 4.6 and 5.2, respectively), with a shallow depth (4.2 km), and whose epicenters were very close to the city of Lorca (< 5 km). The LOR station, located on rock in the city center, registered a PGA equal to 0.27 g and 0.36 g, respectively. The strong ground motion parameters (Arias Intensity, CAV, Spectral Intensity….) give an Imax= VIII for the main earthquake in Lorca. The strong ground motion was conditioned by the directivity effects and the frequency content of the poorly consolidated grounds response. 23 damaged heritage buildings (mostly churches) were inspected "in situ", and analyzed with structural data, fault type and mechanism, and bracing and reinforcement/reconstruction measures. The structural damages were partial collapses (roofs, towers, walls), cracks and collapses (arches, vaults, walls). Faces and ornaments detachments caused damages (particularly to roofs). The excessive rigidity, the lack of connection between vertical and horizontal elements, the elements orientation with respect to the strong ground motion's dominant direction and the existence of a precursor foreshock were the main causes of the damages.

Keywords: 2011 Lorca earthquakes, cultural heritage damage, source directivity effects,

1. INTRODUCTION

The main aspects that are traditionally considered as influential on how and why historical buildings are damaged during an earthquake are: the building proximity to the focus (related to the shaking suddenness), the geological characteristics that locally modify the intensity and frequency content of the ground motion, the duration of the shaking (taking into account foreshocks and aftershocks), the building constructive characteristics (materials, structural system, plan and height configuration, etc.) and the building state of maintenance.

On May 11th, 2011 at 15:05, UTC (17:05 local time), a small earthquake with a moment magnitude (Mw) of 4.6 took place beneath the city of Lorca (Southeast Spain), causing minor damages. The seismic series' main earthquake (a relatively small earthquake of magnitude Mw 5.2) took place at 17:47 (UTC), killing nine people, and wounding nearly 300. Initially the National Geographical Institute (IGN) assigned macroseismic intensities of VI and VII (EMS scale) for the biggest events in the city of Lorca. In spite of the low magnitude of the main earthquake, the damages to the buildings were massive: nearly 80% of the buildings were affected at different levels. The safety inspection (based on the damages severity and extent) of 6416 buildings of the existing 7890 in the city showed that 4035 suffered minor damages (EMS grades 1-2), 1328 suffered moderate damages (grade 2-3), 689 suffered from moderate to serious damages (grades 3-4), and 329 had to be demolished (grades 4-5) (Fig. 1). The main shock was followed by 113 aftershocks during the first month, 80% of them during the first seven days.

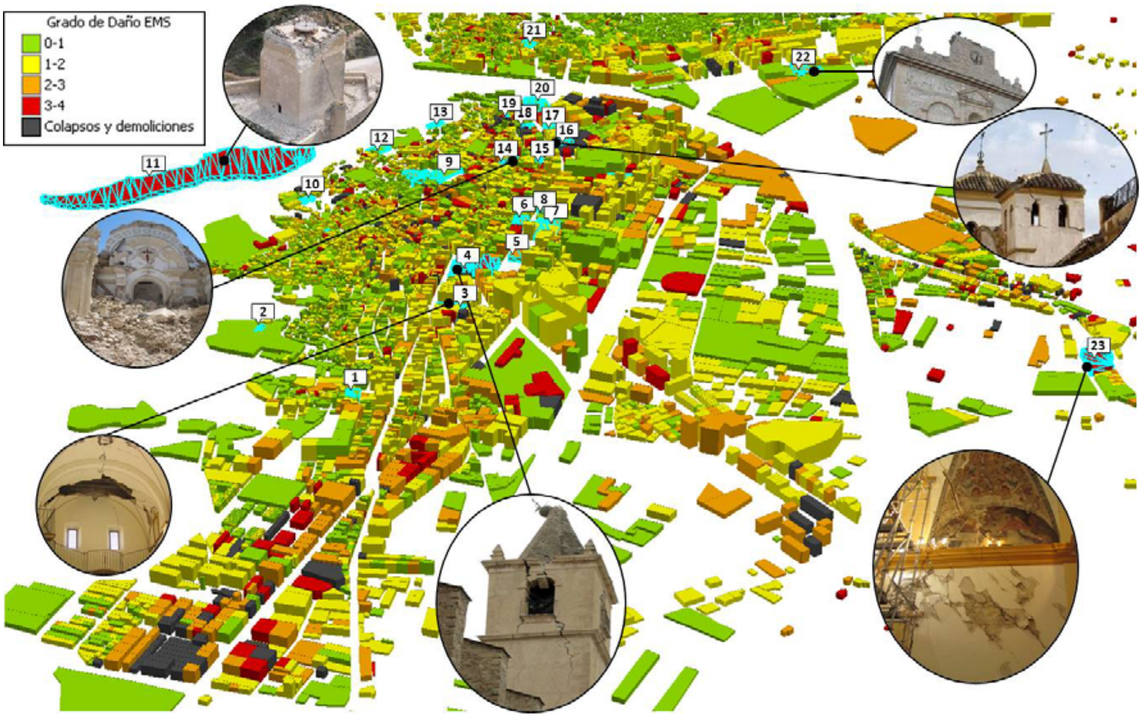

Figure 1. Distribution of the damaged buildings in Lorca and the 23 analyzed historical buildings [1) Church of San Jose; 2) Hermitage of Calvario; 3) Church Nª Sª del Carmen; 4) Church and convent of San Francisco; 5) Guerra theater; 6) Casino; 7) Church of San Mateo; 8) Guevara Palace; 9) Collegiate church of San Patricio, Granary and Consistorial house; 10)Church of San Pedro; 11) Castle (towers and walls); 12) Church of Santa Maria; 13) Church of San Juan; 14) Church of Santiago; 15) House of the Irurita family; 16) Church of Santo Domingo and Chapel of Rosario; 17) Archeological Museum; 18) House of the Mula family; 19) Portico of San Antonio; 20) Palace of la Merced; 21) Church of San Cristobal; 22) Church of San Diego; 23) Virgen de las Huertas Sanctuary].

The seismic series has been re-localized (López-Comino et al., 2012) at the fault of Lorca-Totana, a segment of the active fault of Alhama de Murcia, with a maximum potential of magnitude Mw 6.7, and an average recurrence interval of 2000-5000 years (García-Mayordomo and Martínez Díaz, 2006). In this segment of the fault several historic earthquakes took place, as the ones of 1579, 1783, 1818 and 1907, with EMS intensity of VI-VII and the one of 1674 with an intensity of VIII. Recently, three small earthquakes had occurred near Lorca (epicentral distance < 20 km), the one of Mula, 1999; SW of Bullas 2002, and La Paca, 2005, with magnitudes Mw of 4.7, 5.0 and 4.8, respectively, and maximum intensities between VI and VII (Benito et al., 2007).

During the main earthquake of 2011, the peak horizontal acceleration values (PGA 0.37 g) and velocity (PGV 35.4 cm / s), registered at the seismic station of Lorca (LOR), located on rock in the central-north part of the city, can classify the ground motion as "*severe*" in terms of the Shake-Map classification (Wald et al., 1999). These peak ground motion values would correspond to an intensity of grade VIII (MM scale. Two hours before a low magnitude foreshock took place (Mw= 4.6) and peak values PGA= 0.29g and PGV= 13.76cm/s, which caused several damages and influenced the buildings' response during the second earthquake. These maximum ground motion values can be well explained taking into account the combination of the following factors: (i) the epicenter's proximity to Lorca (<5 km), (ii) the shallowness of the fault (4.6 km) and (iii) the strong directivity effects due to the propagation of the rupture front and due to the fact that the displacement direction at the source is aligned in the direction to the area of Lorca. López-Comino et al. (2012) calculated a rupture of ~ 5 km in length, with direction NE-SW, which is similar to the main direction of the aftershocks distribution. These authors estimated the directivity effect and suggested that the rupture propagated clearly in Lorca direction.

Most of the city of Lorca is founded on sedimentary soils, with a very heterogeneous local structure formed by a succession of alluvial terraces and systems of colluvial deposits, dating from the Pliocene to the present time (Navarro et al., 2012). These soil conditions of the urban area of Lorca have influenced the shaking characteristics, causing a heterogeneous spatial distribution of the severity of the seismic shaking. Most of the historical buildings are distributed (Fig. 1) on the quaternary soils zone, and some of them on hard soils, which were less damaged.

This report aims to analyze the main causes for the damages caused by the seismic series of 2011 to 23 historical constructions of Lorca, revising the damages caused during historic earthquakes, analyzing ground motion data, data of inspections “in situ”, and detailed reports in order to take reinforcement or reconstruction measures.

2. AN HISTORICAL PRECEDENT: THE EARTHQUAKE OF 1674

The city of Lorca has been affected by destructive earthquakes with epicenter close to the city (~37.68N, 1.70W) on several occasions. The first earthquake that proved to cause damages (I= VII) was on January 30th, 1579. Premonitory shakings took place, at least during the series of 1674 and 1818.

In the case of the series of 1674 the similarity of the damages caused to the cultural heritage with the series of 2011 is striking. The main earthquake took place on August 28th at 21h 30m, reaching an intensity of VIII (EMS). There were several felt foreshocks, being the most important those on August 9th and 10th with intensities of VI and V-VI, respectively: the one on August 9th was “*very big and sudden and it broke some houses …//* the citizens were terrified by the event” (intensity ≥ VI). It also had sensed aftershocks for two months, being the most important those on August 28th and 29th (both of I=VII) and those on September 9th and on October 5th (of I=VI-VII) (Martínez-Guevara, 1985; Vidal, 1986).

According to a 113 pages report, about “*the recognition of damages that this city and its citizens …*” (Municipal Historical Archive), the valuation indicates that, out of the 1859 existing buildings, 95% were damaged, more than 220 of them were destroyed (> 12%) and more than 700 suffered relevant damages. The damages were somewhat bigger than the damages caused by the earthquake of 2011. The main earthquake “*… such a big and horrific shaking took place that destroyed part of this city, killing thirty people. Many of the houses were totally destroyed, and temples and towers were on the point of collapse...”* Another damages were reported in written documents, such as the ones of the watch tower, the water pipe, the public fountain, and the Town Hall, being damage of such magnitude that “*it won’t be possible to repair this city in many years*” (Vidal, 1993).

The main affected buildings were: Serious damages to the Town Hall, the Butcher’s shop, the Public Granery and the Watch tower. The city walls were damaged from the Portico of San Antonio to Puerta Nueva. In the parish church of Santiago the tower and the arches had to be rebuilt, because they were broken, and the chapels fell down. The convents of Nuestra Señora de las Mercedes were destroyed and the convent of Santo Domingo and most of its church, cloister and altar were damaged. The parish church of San Mateo was half destroyed, and the convent of Santa Ana and the hermitages of San Roque and Nuestra Señora were damaged. The parish church of Santa Maria collapsed and the tower was broken. The convent of the nuns of Madre de Dios was also damaged. Indeed, similar damage pattern was observed during reconnaissance of 2011 earthquakes.

3. MAIN FEATURES OF THE MAINSHOCK GROUND MOTION

A record analysis of the LOR station, located on rock in the north-central part of the city, made by Alguacil et al (2012) indicates that the ground motion predominant direction was ~N155E, as shown in Fig. 2. These authors, after checking that the LOR station was not affected by site effects, convolved this record with the transfer functions obtained in 11 sites of the town from their structure Vs and simulated the corresponding accelerograms in these points. The strong ground motion parameters in these points (PGA, PGV, CAV, Arias Intensity, Spectral Intensity, acceleration response spectrum, relative energy input spectrum) have values higher than the ones obtained for LOR. These values correspond to a local intensity of no less than VIII (EMS) if compared to the typical values for 12 sites of I = VIII estimated from the Internet Site for European Strong-Motion Data records.

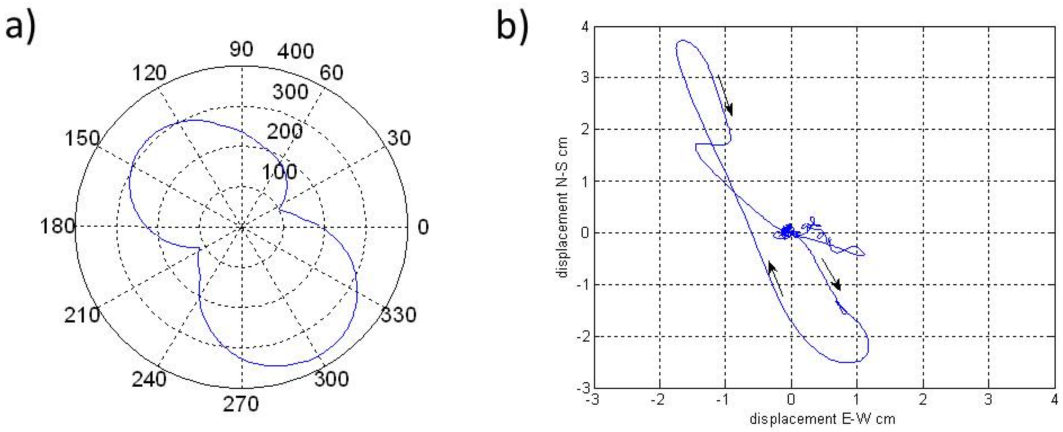

Figure 2. Characteristics of the main earthquake's motion at the LOR station. a) Polar diagram of acceleration. b) Hodogram of displacement (Alguacil et al, 2012).

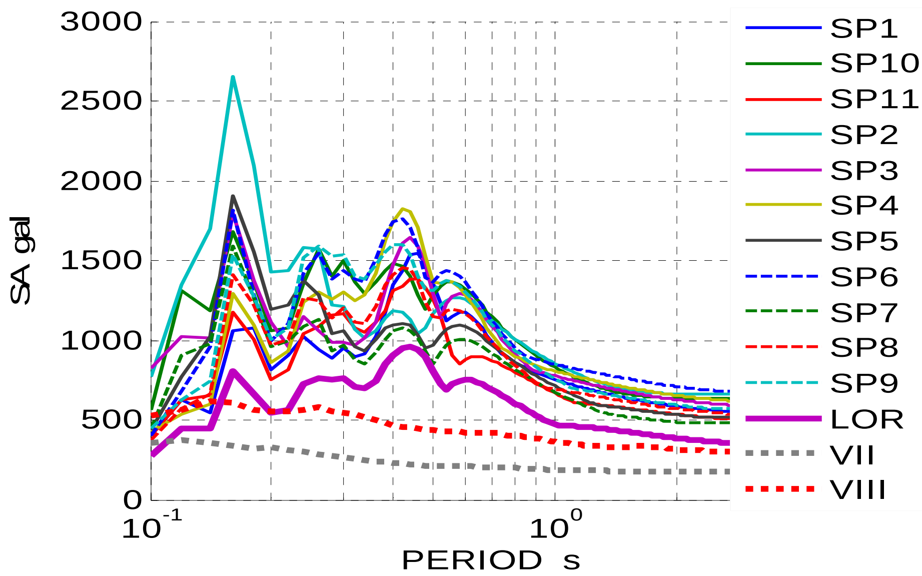

Figure 3. Relative acceleration response spectra with 5% damping for the simulation points (SP) and for the LOR record (rock). For reference, the expected mean response spectra for European earthquakes records where local intensities were VII and VIII are also plotted (Alguacil et al., 2012).

The acceleration response spectra (Fig. 3) for LOR and the simulation points show the motion's characteristics. The amplifications are very significant for periods of ~0.16 s y ~0.4 s, where the relative acceleration reaches 1.5 g in some points and exceeds 1.0 g in most of them in a range from 0.15 s to 0.7 s. The relative significant duration was very small ~ 1s.

4. HISTORICAL BUILDINGS DATA

The data of the 23 out of the 32 more significant historical buildings of the city have been obtained from: "in situ" inspection and damage assessment surveys, and the analysis of different types of data collected in several reports (architectural, historic, damages and restoration and reconstruction measures data).

The historic and architectural data have been obtained from The Autonomous Community of the Region of Murcia, from the Lorca Town Hall and from the Ministry of Culture (Master plan for the recovery of the Cultural Heritage of Lorca[1] (PDRPCL, 2011)). This document is made up of 40 cards containing information about the more relevant building characteristics (year of construction, architectural style, historical outline….), about the damages caused by the earthquakes, both to structural and non structural elements (damages description, pictures and graphics (Fig. 4)), and about the intervention proposals for their recovery (provisional measures and reinforcement and restoration works) along with a cost valuation. These cards are an abstract of the documentation written by the architects and technicians who evaluated the damages and the needed works after the earthquake and the summaries made by the Directorate General of Fine Arts of the Autonomous Community.

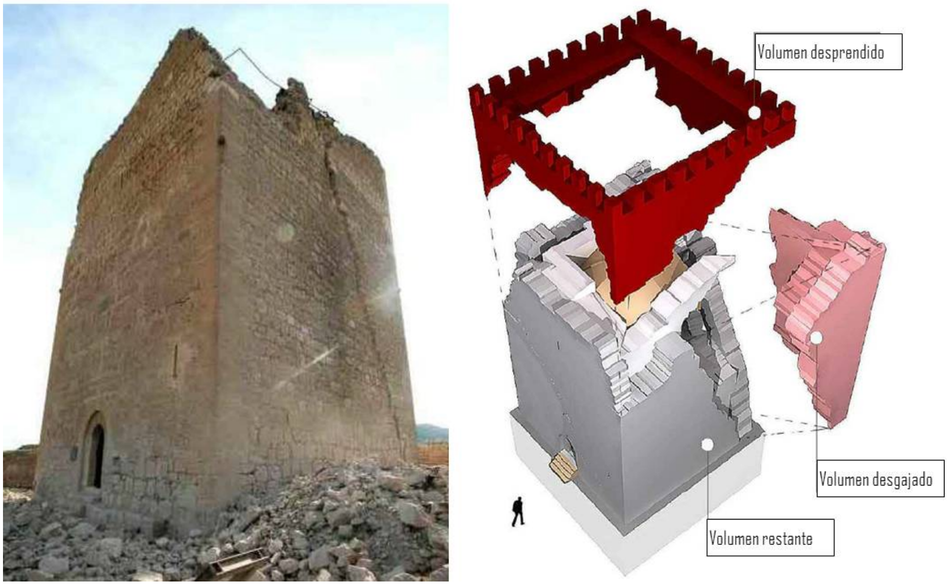

Figure 4. Picture example and illustrative graphic of the damage caused to the Espolón tower (according to one of the fact sheets of the Master plan for the recovery of the cultural heritage of Lorca).

During the evaluation surveys about the damages caused to the Heritage buildings, data on the materials characteristics have been collected (the type of masonry and building materials used in the construction), the geometry (particularly the existence of towers and finishing elements), the plan orientation, the reinforcement elements (buttresses), connections between horizontal and vertical elements of the structure, the layout and characteristics of non-structural walls, the state of maintenance and structure deteroration, and the location and position with adjacent buildings.

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[1] http://www.regmurcia.com/servlet/s.Sl?sit=a,82,c,522,m,1075
[1] http://www.lorca.es/concejaliasyservicios/concejaliasyservicios.asp?id=1547

During these in-situ surveys we have been helped by local and foreign architects, technicians and engineers. The collaboration of the Italian engineering team of NARPIMED project has been remarkable, since they have wide experience in the damages caused to the heritage by earthquakes, such as those in L'Aquila (2009) or Campobasso (2002).

5. CHARACTERISTICS AND CAUSES OF THE DAMAGE ON CULTURAL HERITAGE BUILDINGS

The damage caused by the seismic series of 2011 (and by the one of 1674) show the historical building vulnerability against seismic actions. The historical buildings damages are directly related to the different typologies, the structural complexity, and the conservation and maintenance state, finding cases of a very different nature. This has conditioned different responses to the earthquake, for instance, the response of the big walls built with different materials and heterogeneous constructive systems.

The historical civil buildings having a structural organization with walls in the two directions or a dense compartmentation with structural and non-structural elements have been less vulnerable than the religious buildings. The damages show the heterogeneity of their stones. Many damages to the joints were caused by a lack of connection or by a discontinuity of the constructive elements. In many cases, the damages were due to inadequate alterations that have unbalanced the structure of the constructions. The stair cores have been particularly affected, since they are points of structural discontinuity. (PDRPCL, 2011).

The analyzed Heritage buildings are mostly structures of load-bearing walls made of brick or uncut stone, with ashlar reinforcements in the corners and around the wooden hollows and framework. This type of buildings has got a low ductility. Due to their stiffness they have got high vibration frequencies that make them very vulnerable to close earthquakes (with large high frequencies content). This, added to the lack of connection between the structure vertical and horizontal elements, the geometry and the high weight of the construction materials, has provoked a generalized damage in this type of buildings. A summary of all the damages along with the affected structural elements are collected in Table 2.

The churches have been the more affected heritage buildings, particularly their towers (Fig. 5), and elements such as arches, vaults, domes and roofs. Most of the towers have been seriously damaged. During the second earthquake, the bell towers of the church of San Diego and the sanctuary of Virgen de las Huertas collapsed. Apart from these, the towers of the chapels of Rosario, Santo Domingo, San Francisco, Santiago, San Juan and Santa Maria were seriously damaged and they needed provisional emergency measures (clamps) to prevent their collapse during the aftershocks. Although the towers of San Mateo, San Cristobal, Santa Maria, Nuestra Señora del Carmen and San Pedro were not on the point of collapse, but they suffered shear cracks. The palatial buildings were less affected than the Churches, a fact that may be related to their geometry, weight and smaller size.

The constructive systems used in consolidation and restoration interventions carried out during the last century have not always responded adequately to seismic actions. The use of very heavy concrete for the roofs has raised the efforts and damages. One example is the Church of Santiago, where its partial collapse has provoked the total destruction of the crossing (roofs, domes and vaults collapse). The building roofs underwent several repairs before, including among them the addition of a compression layer of mesh-reinforced concrete, which must have contributed to the damages. The influence of this pathology was proved in similar buildings being damaged by the earthquake of L'Aquila in 2009 (Galli and Camassi, 2009).). The lack of buttresses in that temple area in the direction of the strong motion and the structure weakening (cracks) caused by the foreshock have also influenced the collapse. Although in the rest of the temple the existence of lateral naves and external buttresses avoided the collapse, paraments and buttresses cracks were caused. The tower also suffered damages, such as shear cracks and cornice collapses (Fig. 6).

Figure 5: Damages to the towers of, 1) Chapel of Rosario; 2) San Francisco; 3) Virgen de las Huertas; 4) San Pedro; 5) San Diego (belfry fall); 6) Convent of Clarisas.

5. CONCLUSIONS

According to the analysis, the main factors clearly influencing the damages caused by the earthquakes of 2011 to the Lorca heritage buildings are as follows:

The focuses proximity and shallowness (< 5km) and the fault strong motion directivity in the direction of Lorca have produced high motion values on rock in the city center (PGA = 0.37 g and PGV = 35.4 cm/s) by the main earthquake, in spite of its low magnitude (Mw = 5.2). Moreover, the urban area soil conditions have modified the shaking characteristics resulting in local intensity values of VIII (EMS). The acceleration response spectra in 11 places of the city show very significant amplifications in some of the places for periods of ~0.16 s and ~0.4 s (where the relative acceleration is ≥1.5g) and, in most of them the ra is ≥ 1.0 g in the range of 0.15 s - 0.7 s. The cultural heritage buildings are very stiff buildings that are vulnerable to near field high frequencies.

Table 2. Damages to the main structural elements of the analyzed buildings and zones that have been affected.

	Damage							
Name	**Towers**	**Walls**	**Vaults**	**Domes**	**Roof cover**	**Arches**	**Framework**	**Buttress.**
S.Jose Church		Cracks	Cent. nave		Lateral nave	Cracks	Chorus cracks	
Ch. Calvario		Cracks	Cracks					
Nª Sª del Carmen	Cracks		Breakage & detachment		Central Nave	Cracks and Opening	Breakage and detachments	
Church of S. Francisco	Big Cracks	Cracks and settlements	Cracks and breakages	Cracks and detachment	widespread damages	Cracks and keystone detachments	Chorus Breakage	Cracks
Convent of S. Francisco		Collapses			Partial collapse		Big bend	
Guerra Theat.	Cracks					Cracks		
Casino		Cracks, detachment						
Church of San Mateo	Cracks, cornices fall		Cracks and arches separation		Breakage by tower ashlars fall	Opening		
Guevara Palace		Cracks and fissures				Voussoir fall	Bending and subsidence.	
Collegiate S. Patricio	Rosette detachment	Big cracks	Cracks. Ambulatory Breakage		Breakage by impact	Cracks and keystone take down	Ambulat. Breakage	Carved-stone fall down
Church of San Pedro	Cracks	Cracks and collapses		Cracks and collapse	Damaged	Risk of collapse		
Castle towers, wall	Cracks and detachment	Cracks and detachment	Damages in stairs				Loss of support	
Church of Santa Maria	Cracks and detachment	Cracks and collapses		Cracks in chamber.		Collapses and breakages		Cracks
Church of San Juan	Cracks and detachment	Cracks, detachments collapses		Cracks and collapse	Tower damages	Keystones displacement detachment		
Church of Santiago	Cracks	Cracks	Cracks	Transept collapse	Transept collapse	Cracks and opening		Cracks & displace.
Casa Irurita		Cracks					Detachment.	
Church of Sto. Domingo	Big cracks	Cracks ≈ N-S				Generalized fissures.		
Chapel of Rosario	Tower S. Demolition	Cracks ≈ N-S	Cracks	Broken displaced N-S	Serious damages to dome	Breakages displaced keystone		
Archeological Museum		Cracks and fissures						
The Mula House	Big cracks	Cracks and fissures				Cracks		
Portico of San Antonio	Cracks and battlements fall	Cracks, collapses, & detachments					Loss of support	
Pal. la Merced		Cracks, and detachments						
Church of San Cristobal	Cracks and detachment		Cracks		Breakage by impact	Vaults separation		
Church of San Diego	Belfry collapse	Cracks	Cracks and losses		Central Nave	Cracks and opening		
Virgen Huertas Sanctuary	Small-dome collapse and cracks		Cracks and fissures	Cracks and fissures		Cracks and displacement		Craks

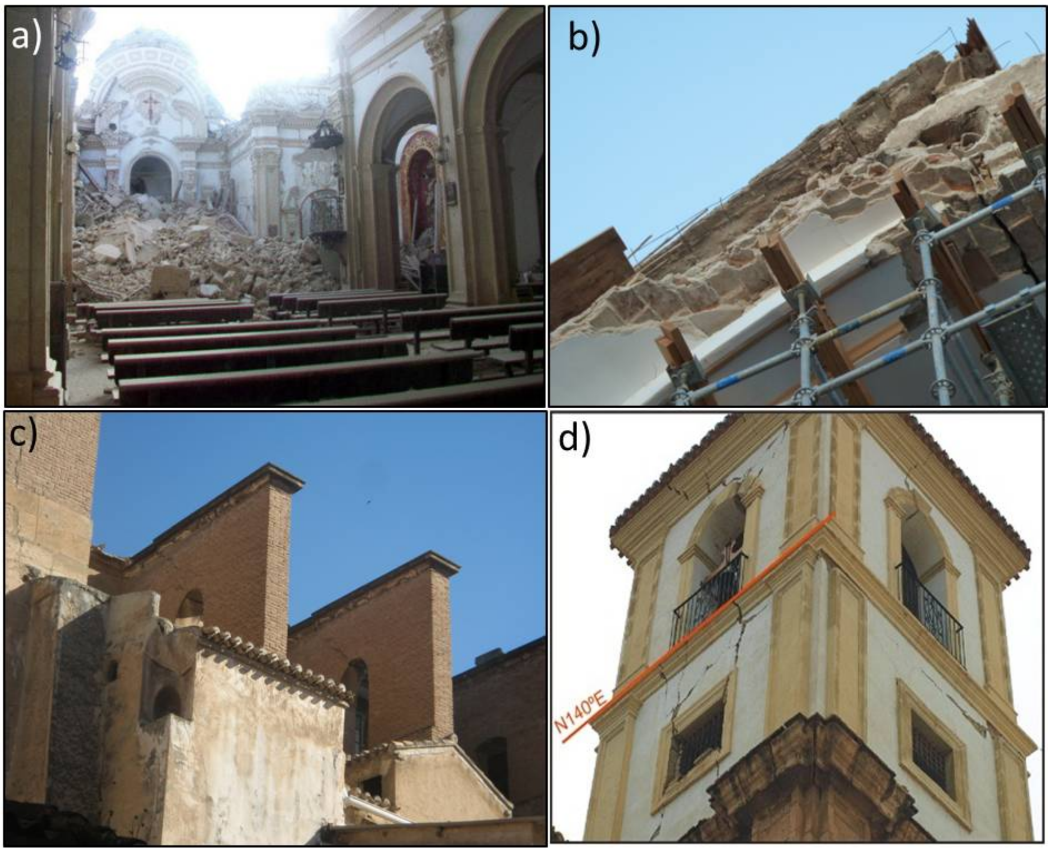

Figure 6: Damages to the Church of Santiago. a) Transept collapse; b) Detail of the RC compression layer of the roof; c) Damages to the buttresses; d) Damages and tower orientation (IGME, 2011)

On the other hand, the first earthquake (M w= 4.6, PGA = 0.29 g and PGV = 13.76 cm/s), causing damages to this type of buildings, increased their vulnerability. The fissures and cracks provoked by this earthquake made possible a later development of them and damage greater than expected. Even the aftershocks increased the already existing damages.

The geometry, stiffness changes and structural elements orientation, particularly in towers, domes and vaults, but also in walls and buttresses, have influenced the damages. It has been proved that the predominant damages are compatible with the strong motion predominant direction (N130E to N160E). The fault mechanisms have been produced in plane (proved by the shear cracks) and out of plane (in walls without flying buttresses or adjacent buildings) and also the ones due to torsion phenomena (more visible in slender and finishing elements).

The main cause of earthquake damage to Lorca heritage buildings has been the lack of connection between vertical and horizontal structural elements in order to support lateral stresses. On the other hand, inadequate alterations, such as metallic bracings, the material combination used in load-bearing walls, or the addition of compression layers of mesh-reinforced concrete to roofs and vaults, have increased the vulnerability of this type of buildings. After rusting and increasing in size, the metallic bracings have broken the stone. The materials combination has provoked their disintegration in load-bearing walls, loosing their lateral resistance. The addition of compression layer in slabs has increased their mass and made them behave as hammers, increasing the damages to the walls and causing the roof collapse (this is the case of the Church of Santiago or the chapel of the convent of Clarisas).

A crucial point regarding structural safety and architectural preservation of the cultural heritage buildings is the possibility to be seismically upgraded with the implementation of strengthening interventions. The severity and cost of the damages caused to the Lorca cultural heritage buildings have proved once more that it's more recommendable to apply retrofit and reinforcement measures to structural and non-structural elements before an earthquake occurs.

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