Chapter

Effects of Earthquakes on Buildings in the Ibero-Maghrebian Region

José Antonio Aparicio Florido

Abstract

The types of damage caused by earthquakes in buildings are closely related to the design and building techniques with which they have been built and the quality of the construction materials used. Most of countries with moderate to high seismic risk areas have implemented earthquake-resistant standards to prevent the collapse of buildings and minimize the severity of the damage. However, every new strong shake that occurs around the world reveals bad construction practices that could have been avoided, and the inadequacy or non-existence of earthquake-resistant standards aimed at reducing vulnerability to non-catastrophic levels. Based on the EMS-98 scale, in this chapter we will analyze three case studies of the Ibero-Maghrebian region that have been using similar construction patterns with similar catastrophic results for buildings despite the different dates in which they occurred and the different earthquake-resistant standards: SW Cape St. Vincent earthquake of February 28, 1969; Al Hoceima earthquake of February 24, 2004; and Lorca earthquake of May 11, 2011.

Keywords: earthquakes, damage, buildings, standards, shear cracks, X-shaped cracks, plastic hinges, soft-story, vulnerability

1. Introduction

The Ibero-Maghrebian region comprises the southern part of the Iberian Peninsula, (including Andalusia, Murcia and Alicante) and North Africa from the Atlas range to the Mediterranean sea, bordering Tunisia to the east and the Atlantic coast of Portugal to the west, embracing Morocco and Algeria [1]. The seismicity of this region is characterized by the N-S to NW-SE convergence between Eurasian and Nubian plates [2]——with a possible rotational axis to the north of Canary Islands—— and by the occurrence of shallow earthquakes (<30 km).

Along this area, between January 1, 1950 and December 31, 2019, 198 earthquakes of magnitude M≥5 took place and, of these, 42 shocks (21%) reached intensities ≥VI (**Table 1**). The most destructive event was that of El Asnam (Algeria) on September 9, 1954 with intensity X-XI [3]. However, the largest earthquake in magnitude was that of February 28, 1969 (M_w = 7.8), located in the Horseshoe Abyssal Plain, southwest of Cape St. Vincent [4]. This one caused a widespread destruction in Portugal, Spain and Morocco, and a moderate tsunami recorded in the tide gauges of Cascais (93.2 cm), Lagos (84.3 cm), Cádiz (28.4 cm) [5], La Coruña (12 cm),

Date	Time	Lat.	Long.	Depth (km)	Int.	Mag.	Epicenter
1950/04/20	17:19:14	339.000	21.000	—	VI	5.1 M_0	El-Gheicha.AL
1951/03/10	10:38:26	375.950	−39.750	15	VII	5.2 Mw	Castillo de Locubán.SP
1951/05/19	15:54:26	375.670	−39.170	19	VII	5.3 Mw	Castillo de Locubán.SP
1953/08/29	14:08:50	358.000	50.000	—	IX	5.2 M_0	Hodna.AL
1954/09/09	09:28:42	360.000	15.000	—	X	6.0 M_0	El Asnam.AL
1954/09/09	01:04:37	362.833	14.667	—	X-XI	6.7 M_0	El Asnam.AL
1954/09/10	05:44:05	366.000	13.000	—	VIII	6.0 M_0	Tenes.AL
1954/10/10	06:01:48	363.000	18.000	—	VI	5.5 M_0	Kerba.AL
1954/10/12	19:23:29	362.500	17.000	—	VII	6.0 M_0	Fodda.AL
1955/06/04	03:41:35	371.333	−36.467	5	VI-VII	5.1 M_0	Armilla.SP
1956/04/19	18:38:54	371.917	−36.833	5	VII-VIII	5.0 M_0	Purchil.SP
1956/08/16	02:09:40	369.100	−86.067	5	VI	5.0 M_0	Gulf of Cádiz
1959/05/24	13:19:38	363.383	45.317	5	VIII	5.1 M_0	Bordj Bou Arreridj.AL
1959/08/23	22:21:30	355.133	−32.267	20	VI	5.4 M_0	South Alboran
1959/11/07	02:32:08	364.000	25.000	—	IX	5.1 M_0	Bou Medfa.AL
1960/02/21	08:13:33	356.517	42.500	5	VIII	5.5 M_0	M'Sila.AL
1960/02/29	23:40:14	304.500	−96.167	—	X	6.0 M_0	Agadir.MR
1961/02/10	18:52:01	417.250	−61.967	—	VI	5.2 M_0	Zamora.SP
1964/03/15	22:30:26	361.317	−77.500	30	VII	6.2 MbLg	Gulf of Cádiz
1965/01/01	21:38:26	357.000	45.000	—	VIII	5.2 MbLg	M'Sila.AL
1967/07/13	02:10:21	355.300	−0.1267	5	VII	5.0 MbLg	Mascara.AL
1967/08/13	22:07:47	432.950	−0.6767	5	VIII	5.3 MbLg	Navarrenx.FR
1969/02/28	02:40:32	359.850	−108.133	20	VIII	7.8 Mw	SW Cape St. Vincent
1973/11/24	15:22:09	361.000	44.000	—	VII	5.1 MbLg	Mansourh.AL
1975/05/26	09:11:49	359.000	−176.000	—	VI	6.7 MbLg	Athlantic Ocean
1980/10/10	12:25:23	361.533	14.467	5	IX	6.5 MbLg	Chlef.AL
1988/10/31	10:12:59	364.433	26.083	13	VII	5.4 MbLg	Blida.AL
1989/10/29	19:09:14	367.483	24.333	5	VIII	5.7 MbLg	Mediterranean-Algeria
1989/12/20	04:15:05	372.250	−73.917	23	VI	5.0 MbLg	Ayamonte.SP
1992/10/23	09:11:08	312.200	−43.567	7	VI-VII	5.3 MbLg	Morocco
1992/10/30	10:44:01	314.117	−43.833	21	VII	5.1 MbLg	Morocco
1993/12/23	14:22:35	367.800	−29.367	8	VI-VII	5.0 MbLg	Berja.AL
1994/08/18	01:13:07	354.783	−0.1417	5	VII	5.7 MbLg	Mascara.AL
1997/05/21	23:50:45	427.833	−72.583	13	VI	5.1 MbLg	Triacastela.SP
2003/05/21	18:44:19	368.187	37.203	—	IX-X	6.6 Mw	Boumerdès.AL
2004/02/24	02:27:46	351.563	−39.841	—	VIII	6.2 Mw	Al Hoceima-Tamassint.MR

Date	Time	Lat.	Long.	Depth (km)	Int.	Mag.	Epicenter
2004/12/04	10:29:59	349.796	−29.722	6	VI	5.0 Mw	Hasssi Berkane. MR
2006/03/20	19:44:23	366.736	55.604	—	VII	5.1 Mw	Bejaia. AL
2006/04/02	06:44:31	349.373	37.942	—	VI	5.4 mb	Bou Saada. AL
2008/02/01	07:33:41	368.223	35.288	12	VI	5.0 mb	Boumerdès. AL
2011/05/11	16:47:26	377.175	−17.114	4	VII	5.1 Mw	Lorca.SP
2016/01/25	04:22:01	356.004	−38.056	12	VI	6.3 Mw	South Alboran

Table 1.
Earthquakes felt with intensity ≥ VI in the Ibero-Maghrebian region between January 1, 1950 and December 31, 2019. Source: Instituto Geográfico Nacional (IGN).

Chipiona (30 cm), Santa Cruz de Tenerife (0.17 cm) and Casablanca (120 cm) [6]. On the other hand, the shallowest earthquake (depth = 1.4 km) and the second most damaging in this list, with ≈15,000 dead and 70% of all new buildings ruined [7], was that of February 29, 1960 in Agadir (Morocco), considered as a moderate earthquake compared to its magnitude M_0 = 6.0.

These initial considerations show us that the effects of earthquakes are not merely a proportional relationship between magnitude and intensity; moreover, there are some other parameters and more deterministic in terms of vulnerability, such as the distance from the epicenter to populated areas, the depth of the hypocenter, the geological characteristics of the soils and, mainly, the quality of the buildings regarding to the construction techniques, pattern, materials and antiseismic design, which is the subject of this chapter.

2. Method of analysis

To explain the effects of earthquakes on buildings using the same analysis criteria, we will use as reference the 1998 European Macroseismic Scale (EMS-98) [8], based on the MSK scale, consisting of twelve incremental levels of intensity in Roman numerals (I-XII) and six vulnerability classes identified by the first letters of the alphabet (A, B, C, D, E and F). The scale also distinguishes and describes four types of structures (masonry, reinforced concrete, steel and timber) of which we will focus on those of masonry and reinforced concrete (hereinafter, RC) without earthquake-resistant design (ERD), the most common in the Ibero-Maghrebian region. Both types of construction, masonry (non-engineered) and reinforced concrete (engineered), present a vulnerability class A, B or C; classes D, E or F, require the implementation of moderate or high ERD measures or the use of steel or timber as the main construction material, unusual within the study area. Here, as we will see later, the buildings share similar construction patterns and offer up the same level of resistance: vulnerability class A or B for masonry buildings, with the exception of those made of massive stone or ashlars (class C), and vulnerability class C for RC buildings. We will prove, for example, how a building of class A located in the Algarve (Portugal) is very similar in terms of construction pattern to another of equal vulnerability in Ait Kamra (Morocco); or how a building of class C in Lorca (Spain) can be damaged in the same way as a similar one in Al Hoceima.

With respect to the classification of damage, which is carried out by direct observation in the field, the EMS-98 scale considers five levels: grade 1, negligible to slight damage; grade 2, moderate damage; grade 3, substantial to heavy damage;

grade 4, very heavy damage or partial collapse; and grade 5, destruction or total collapse. Buildings with a grade of damage 1 to 3 do not result in structural or significant structural damage, being easy to repair and recover, while those of grade 4 or 5 have severe or complete structural damage and are difficult or impossible to recover. In this scientific contribution we will explain these effects in detail based on three of the most destructive and best documented earthquakes recorded in the study area: southwest Cape St. Vincent, 1969; Al Hoceima, 2004; and Lorca, 2011.

3. Documentary sources

The analysis and description of damage from these selected seismic events is based on several documentary sources: available unofficial field reports, official reports from public authorities, photographs showing damage to buildings, and information provided by news agencies and newspapers.

In the case of the 1969 earthquake, our main source for the area of Portugal is the technical report carried out by the seismologist Mário de Vasconcelos Trêpa [9] and, for the case of Huelva (Spain), the official reports of Isla Cristina Town Council. Regarding the 2004 Al Hoceima earthquake, the analysis will be based on the field report made by the technical architect Patrick Murphy Corella [10]. Finally, with respect to the 2011 Lorca earthquake we will take as documentary source our own field report and photographs taken by emergency managers of the Instituto Nacional para la Reducción de los Desastres (IERD) [11].

4. The February 28, 1969 earthquake

The 1969 SW Cape St. Vincent earthquake took place on Saturday, 28th February, at 02.40.32 UTC (t_0), and was located in the Horseshoe Abyssal Plain, coordinates 35.98° N 10.81° W, 200 km away to the SW of Cape Saint Vincent, with hypocenter at 20 km depth. Its high magnitude Mw = 7.8 (IGN) caused seismic waves to heavily shake Portugal, Spain, and Morocco. Moreover, this seismic event is associated with a reverse faulting between Azores and the Gulf of Cadiz in the western part of Africa-Eurasia plate boundary, which generated a moderate tsunami recorded in several tide gauges, strongly damaging the Norwegian tanker "Ida Knutsen" while sailing in deep waters [12].

4.1 Effects in Portugal

4.1.1 Algarve: an example of bad behavior of buildings of vulnerability A or B

The greatest damage to buildings in Portugal was registered in the Algarve region, with total or partial collapses spread over different locations, amplified by the so-called *site effect* [13, 14], that is, the amplification of the seismic waves due to the geological characteristics of soils in superficial layers and the soil-structure interaction of buildings. Settlements built on younger tectonic formations, such as poorly consolidated alluvial soils, felt the shakes more strongly [15], increasing the vulnerability of traditional constructions made with extremely poor materials and techniques. Most of them had one or two floors supported on load-bearing walls made of fieldstone or adobe masonry bound with mud mortar, clay or without mortar. These external walls, quite thick and most often strengthened with double-leaf shape (two walls facing each other, barely joined by a poor mortar), supported a gable roof made of wooden logs or struts under a bed of reeds covered with tiles or zinc plates. Therefore, they must be classified as structures of vulnerability class A, and hence the effects in Castro Marim, Barão de São Miguel, Vila do Bispo, Bensafrim, Fonte de Louzeiros or Silves.

The damage reached greater severity and geographical extension within a radius of 50 km around Cape St. Vincent. In Silves, several houses collapsed, and lateral loads produced many shear cracks, overturning or toppling of load-bearing walls, corner failures and large cracks in the walls of the castle. **Figure 1** shows shear cracks, with detachment of little pieces of plaster and partial toppling of external wall from the upper floor, after loss of connection and possible mutual pounding of adjacent buildings with roofs at different levels, in a three-story building of class B (grade 3). Bensafrim, 26 km from Silves and closer to Cape St. Vincent, was one of the towns hardest hit by the earthquake. More than twenty houses were destroyed and around forty suffered the typical damage of buildings of class A: loss of connection between load-bearing walls, corner failure, overturning or toppling of external walls, detachment and fall of outer leaf, X-shaped or diagonal cracks, fall of plaster, and roof collapse. The primary school, recently built with RC (class C), had cracks in several parts (grade 3). An example of corner failure with partial roof collapse is described in **Figure 2**, which should be assessed as grade 4 in building of class A. The same description can be made for Odiáxere, a *freguesia* (municipality) of Lagos council, at the distance of 7 km from Bensafrim.

In Vila do Bispo, 8 km from Sagres, many houses of class A were partially or completely collapsed and turned into rubble (**Figure 3**), with a level of destruction similar to Bensafrim. **Figure 4** shows an example of façade overturning pulling down the roof and causing a complete collapse of the structure (grade 5). In other photographs we can clearly observe damage of grade 3 in corner failures (**Figure 5**) and grade 4 in the toppling of external wall, seriously affecting the roof (**Figure 6**). Also, the upper body of the church tower of Nossa Senhora da Conceição, built with massive stone, ashlars and burnt clay/sand bricks showed a progressive X-shaped

Figure 1.
Silves, building of class B with damage of grade 3: (a) shear cracks with detachment of little pieces of plaster; (b) partial toppling of external wall. Source: IPMA.

Figure 2.
Bensafrim, building of class A with damage of grade 4: (a) advanced corner failure and toppling of external wall with partial roof collapse; (b) loss of connection and drift between load-bearing walls; (c) generalized detachment of plaster. Source: IPMA.

Figure 3.
Vila do Bispo, general overview: (a) loss of the outer leaf of load-bearing walls and detachment of plaster; (b) partial toppling of façade wall, pulling down part of the roof; (c) good behavior of a recent construction (class B); (d) simple overturning of a freestanding masonry wall; (e) adobe house without apparent damage. Source: IPMA.

Figure 4.
Vila do Bispo, total collapse of building of class A made of mixed fieldstone and adobe masonry, mud or clay mortar and roof supported by wooden logs and bed of reeds (grade 5). See the doble-leaf shape on an interior load-bearing wall remaining standing. Source: IPMA.

Figure 5.
Vila do Bispo, building of class A with damage of grade 3 due to loss of connection between load-bearing walls and corner failure (left). This two-story house was repaired and is currently in use (right). Sources: IPMA/ Google Earth.

crack and fall of pinnacles [15], which means damage of grade 3 in buildings of class B. In summary, the traditional construction techniques based on adobe masonry and clay mortar showed a high vulnerability and weakness (**Figure 7**).

Several houses were totally collapsed in Sagres and many others suffered damage of grade 2 or 3 in buildings of vulnerability class A. In **Figure 8**, one single-story house with gable roof shows shear cracks, detachment of cornices and tiles, partial roof collapse, loss of connection between load-bearing walls and drift from the façade with risk of overturning (grade 3). Also, in Raposeira, 5 km east from Vila do

Figure 6.
Vila do Bispo, building of class A with damage of grade 4: (a) loss of connection between load-bearing walls; (b) toppling of external wall; (c) collapse of roof made of wooden logs and bed of reeds. Source: IPMA.

Figure 7.
Vila do Bispo, typical house of vulnerability class A built with raw materials: load-bearing walls made with adobe bricks, doors and windows with lintels, and wooden logs supporting a tiled roof over a bed of reeds. Source: Google Earth.

Bispo, a crack arose on the façade of the hermitage of Nossa Senhora de Guadalupe, running from the gable to the apex of the ogival arch of the entrance, from top to bottom, crossing the rose window [15]. This chapel dates from 14th century and was built with load-bearing walls made of massive stone, with pillars of ashlars embedded and supporting a ribbed vault built with the same material. The entire structure was reinforced with solid buttresses around the side walls and toothed ashlars in the corners; therefore, it should be assessed as damage of grade 2 in a building of vulnerability class C.

Figure 8.
Sagres, building of class A with damage of grade 3: (a) loss of connection of load-bearing walls with drift of façade, and (b) detachment of cornices and tiles with partial roof collapse. Source: IPMA.

A similar description could be made for Portimão, located 40 km to the east. According to Trêpa's report, this town was "undoubtedly, the most affected city in the whole territory". However, there is no specific information of damage that would allow us to confirm this statement. **Figure 9** shows the partial detachment and toppling of the outer leaf of the external wall from the second floor of a two-story building of class B, with the subsequent fall of a cornice section and detachment of tiles (grade 3) due to a hammering effect between the wooden joists supporting the roof and the top of the load-bearing walls.

4.1.2 Fonte de Louzeiros: the maximum intensity in the whole macroseismic area

Fonte de Louzeiros is a small rural hamlet located 7 km at east of Silves. In this settlement of sixteen houses at the time, the most of buildings were total or partially collapsed. The earthquake caused all type of damage mentioned above: X-shaped cracks, corner failures, overturning of load-bearing walls and roof collapses; almost no house could be rebuilt. As an exceptional example, in **Figure 10** we can see one of the few buildings left standing and showing the patched damage of a corner failure. About 95% of these single-story buildings of vulnerability class A suffered damage of grade 5.

Some seismologists have assigned to this place intensity VIII, the maximum level of destruction in the whole macroseismic area [16], although other researchers extend this isosist, in general, to the Algarve region [4] or enclose it to the Cape St. Vincent and surroundings areas [9, 15, 17, 18]. But this particular case of Fonte de Louzeiros, with a total destruction of buildings of vulnerability class A, does not correspond to an area of intensity VIII but rather to intensity IX, or at least VIII-IX [19]. Therefore, it is consistent to raise the damage recorded in Fonte de Louzeiros to intensity VIII-IX, where "a bombing would not have been worse", literally "wiped off the map", as defined by the *Diario de Lisboa* on March 2, 1969.

4.1.3 Alentejo coast, Setúbal and Lisbon: the transition to vulnerability class C

Outside the Algarve region, the intensity of the damage decreases slightly, except along the Atlantic coast between Aljezur and Setúbal, where the effects reached

Figure 9.
Portimão, two-story building of class B with detachment and toppling of the outer leaf of the external wall on the second floor, due to a hammering effect between the wooden joists supporting the roof and the top of the load-bearing walls (grade 3). The lack of shear cracks indicates a ground displacement from back to front. Source: IPMA.

Figure 10.
Fonte de Louzeiros, building of class A rebuilt after the 1969 earthquake, showing the repair mark of a corner failure (dotted line). Inside the white circle is visible the red color of the clay used to join the adobe masonry. Source: Google Earth.

intensity VII, or VI-VII in the Lisbon district. In São Teotónio, Longueira, Vila Nova de Milfontes, Cercal and Sines, midway between Cape St. Vincente and Setúbal, many houses of class A collapsed. The rural village of Longueira, completely built with the same construction techniques of the Algarve, was razed; and the same situation occurs in Vila Nova de Milfontes and Cercal, where only the RC buildings (class C) performed well. In Odemira, partial roof collapse can be observed in buildings of class A (grade 4), due to the hammering effect of the wooden logs supporting the roof against the top of the load-bearing walls, to which they were not well anchored (**Figure 11**).

Compared to the previous locations, the city of Sines felt abnormally strong vibrations of soils, probably influenced by geological conditions and site effect. Some houses of class A or B total or partially collapsed (grade 4 or 5) and other buildings of class C as the City Hall, the church of São Salvador and the hospital suffered significant damage with fall of apparently non-structural elements. Further north along the coast, in Grândola, 38 km northeast, buildings of class B (simple stone) had a good behavior with some shear cracks and detachment of non-structural elements (grade 1 to 3), but twenty houses of class A (adobe masonry) had to be rebuilt of demolished because of corner failures, overturning of load-bearing walls, roof collapse and fall of plaster and cornices (**Figure 12**).

Finally, in Setúbal and Lisbon the structures of vulnerability A and B had been widely replaced a long ago by those of class C (monumental and RC buildings), contributing to a lower level of destruction. Even so, in Setúbal some old houses collapsed, and shear cracks arose everywhere. Ceramic shops were specially shaken, with high material losses of facilities and merchandise. The factory of Pinhal Novo, built of RC supporting structure with hollow clay floor slab blocks over RC beams (class C), became a mountain of debris (grade 5), due to the scarce rigidity of column-beam joints and the use of smooth steel rods (not corrugated) within the core of RC frames. The information available for Lisbon allows us to assess damage of grade 2 in buildings of class C and grade 3 for class B, with a lot of cars buried in rubbles by the fall of plasters, bricks, cornices, eaves, chimneys, balconies, windows and other non-structural elements form buildings of class C, with similar consequences as we will see later when analyzing the 2011 Lorca earthquake.

Figure 11.
Odemira, damage of grade 4 in adobe masonry house of vulnerability class A: (a) detachment of plaster; (b) partial roof collapse due to the strong pounding of wooden logs against the top of the load-bearing wall. Source: IPMA.

Figure 12.
Grândola, damage of grade 4 in a house of class A (adobe masonry): (a) advanced corner failure not compromising the roof; (b) general detachment of plaster. Source: IPMA.

4.2 Effects in Spain

4.2.1 Severe damage limited to Guadiana/Guadalquivir strip

In Spain, as happened during the earthquake of November 1, 1755, the shocks were felt most strongly in western Andalusia, near the border with Portugal, along the strip between the rivers Guadiana and Guadalquivir. It is undoubtedly due to the increasing human settlement on young soils formed by sedimentary alluvial deposits from both rivers, tributaries streams and other intermediate rivers such as Tinto and Odiel. In the city of Seville, the seismic event caused a widespread partial fall of non-structural elements in buildings of class B or C (as in Setúbal, class A is not very representative, practically nonexistent) and moderate damage not higher than grade 3 to monumental buildings (class C) as La Giralda, Torre del Oro, Alcázar, Museum, Navy Command Headquarters, City Hall, Telefónica building, Post Office building and Cathedral.

However, in the western half of the province of Huelva, the level of damage was remarkably similar to that of the Algarve region, due to the analogy between the construction patterns, especially with regard to buildings of class B or monumental buildings of class C (adobe masonry structures were less common in this geographical area). About 274 buildings in the city of Huelva were damaged, 1 completely ruined and 18 partially collapsed. Several photographs published in newspapers allow us to diagnose grade 3 in residential buildings of class B and grade 2 and 3 in monumental buildings of class C (Cathedral, Iglesia de la Milagrosa, the Town Hall, etc.). In the surrounding villages little damage of grade 4 or 5 was recorded, with the exception of Ayamonte and Isla Cristina.

4.2.2 Widespread damage to buildings of class A and B in Isla Cristina

Isla Cristina and Ayamonte are two Spanish towns located in the province of Huelva, at the mouth of the Guadiana River, very near the border with Portugal just 10 km from Castro Marim. Obviously, there was a very close relationship between the damage caused by the earthquake and the fact that both towns were settled over sedimentary soils. In Ayamonte, a few houses that already showed a previous state of abandonment collapsed, and only were recorded a few cases of fall of beams and roofs, or cracks in some load-bearing walls and infill partitions. But in Isla Cristina, 7 km away, damage of grade 4 and 5 was widespread.

The historical and archival reports provided to us by the Town Council of Isla Cristina ——unfortunately, there are no photographic documents—— are not very descriptive in relation to the damaging effects in this place. Three expert teams that carried out the disaster evaluation limited their analysis to estimating that 65% of the total number of buildings in this municipality were damaged (≈ 350 houses), resulting 21 of them in partial or total collapse and completely uninhabitable (grade 4 or 5). With this scarce official information available and based on the photos published by the press, we can compare this level of destruction with this one observed in Bensafrim or Vila do Bispo, in the Algarve region, but in an area 130 km further away from the epicenter with respect to the Portuguese towns here mentioned. Therefore, the site effect is also evident in the Guadiana estuary.

4.2.3 Clocks

The earthquake took place in origin (t_0) at 02.40.32 UTC (IGN), but P waves reached the seismographic stations of Spain and Portugal at different times depending of the epicentral distance (UTC): Lisbon, 02.41.20; Coimbra, 02.41.41; Porto, 02.41.52; San Fernando, 02.41.30.5; Toledo, 02.42.07; Canarias, 02.42.08; Granada, 02.42.09; and Barcelona, 02.43.10. In San Fernando we take as reference the record of the official seismic bulletin of the Real Observatorio de la Armada (ROA).

Just at 03.45 suddenly stopped the clocks of the City Halls of Cádiz, El Puerto de Santa María and the Compañía de Seguros building located in Plaza de Neptuno, Madrid. In Lisbon, the clock on the main façade of the Estação do Sul (railway station) stopped at 03.44 local time (+1 UTC), although the time gap is probably due to a lack of synchronization between local and UTC time. In Huelva, the clock of the Catedral de la Merced stopped at 03.41 and in Palencia, 860 km from the epicenter, the City Hall clock also stopped at 03:45, because the machinery had come out of its gear due to the strong motion. Surely this was the same cause that made all the other clocks to stop.

4.3 Effects in Morocco

The earthquake caused strong shakes in Marrakech, Safi, Casablanca, Tétouan, Rabat, Salé and Tangier, among other sites in Morocco. In Salé, two houses that already had a previous state of ruin collapsed, and in Rabat some houses in the surrounding area (class A) were ruined. However, in Agadir the earthquake had not been felt.

The available macroseismic data from Morocco is very scarce, mainly due to the coincidence of an episode of severe flooding caused by a powerful storm that left torrential rain, flash floods and rivers bursting their banks along the Atlantic coasts and in the Moroccan Atlas. In the region of Casablanca-Settat (formerly named Dukala-Abda) large areas of crop fields were flooded and affected by landslides, with three villages submerged under waters. In the city of Salé, a short distance north of Rabat, a house collapsed due to the riverine flooding of the river Bou Regreg, forcing the evacuation of its residents. In Kenitra, 35 km north of Rabat, the roads were cut by flooding and 100,000 hectares of crop fields were devastated by the rainfall. Also, 39 houses were washed away by the floodwaters 120 km north of Rabat, leaving some villages isolated. Further inland, in the middle of the Atlas, 95 houses were left with water over rooftops. These widespread floods in much of the

Moroccan territory made communications difficult, and the authorities and rescue teams focused on the effects of the floods rather than the effects of the earthquake. As a consequence, under the impact of two natural phenomena at the same time and along de same disaster area, it is difficult to distinguish which damages are due to the floods, to the earthquake or to the combined effects of both episodes.

5. The Al Hoceima earthquake of February 24, 2004

The Al Hoceima earthquake of February 24, 2004 took place at 02:27:46 UTC, at coordinates 35.1563 N -3.9841 W, south of the Alboran Plain, in the Mediterranean Sea near the Strait of Gibraltar, with epicenter north of Tamassint (Morocco). The magnitude of this seismic event was Mw = 6.2 (IGN) and there are no data about its depth, so it is estimated that it must have been very superficial <5 km. To have an approximate idea of the superficiality and energy released, the main shock was followed by more than 760 aftershocks over Mw>3 during the following two months.

5.1 The failure of traditional construction patterns

This earthquake hit the province of Al Hoceima, especially the city so named, the municipality of Imzourem and the villages of Ait Kamra and Izemmouren. The rural houses in this geographical area of Morocco, most of them of vulnerability class A, were built using the traditional construction pattern, very similar to those we have just highlighted in the most rustic areas of the Algarve, with more emphasis in Fonte de Louzeiros: single-story load-bearing walls made with unworked raw materials and unskilled masonry techniques, supporting a brittle roof of wooden logs in parallel under a bed of reeds tied together with rope or wire, all covered by a layer of water-repellent mortar and, occasionally, with a plastic film interposed acting as waterproof element (**Figure 13a**). The load-bearing walls were made up

Figure 13.
Ait Kamra, traditional house pattern: (a) partial collapse showing the doble-leaf load-bearing walls, fieldstone masonry bonded with mud mortar and roof of wooden logs and canes covered with a plastic film (blue) and layer of water-repellent mortar (grade 4, class A); (b) handmade joist of hollow bricks assembled with a single steel rod. Source: P Murphy.

of two faces of field stone masonry (double-leaf) not anchored between them, and poorly bonded with high porosity and low adhesion mud mortar. The bending of the walls in both directions due to reverse horizontal forces caused the inner detachment of the double-leaf masonry and the subsequent bowing, peeling, and overturning or collapse of the external skin. Shear cracks also caused widespread wall collapses and massive corner failures and fall of roofs, pulling down huge amounts of debris (**Figure 14**). The use of hollow bricks assembled with a single steel rod to form a handmade joist as reinforcing element for the roof did not provide greater rigidity or better connection between roofs and load-bearing walls (**Figure 13b**).

5.2 X-shaped damage, a seismic evidence

Regardless of the function of the walls (infill, load-bearing, retaining, etc.), type of building materials (adobe, stone, brick, gray concrete block…) and vulnerability class (A, B, C…), not all cracks should be exclusively interpreted as a result of seismic shaking. In general, wall cracks are caused by the effect of five recognized forces: tension, compression, bending, torsion, or shearing. But only when cracks have a diagonal shape it can be inferred that they have been generated by shear stress or a combined effect tension-shearing or bending-shearing. Shear or diagonal cracks may be due to earthquakes, but also——and most frequently——to a slope in the ground, poor foundations, landslide, soil composition (i.e., expansive clays), geological conditions, etc., which can lead to subsidence or settlement processes.

In April 2019, during a brief field visit to the Roman ruins of Baelo Claudia (Tarifa, Spain), an ancient city where some geologists have believed to find evidence of great destruction caused by a sequence of earthquakes between the 1st and 3rd centuries BC, we certainly observed shear cracks in the *summa cavea* of the theatre, bowing of a load-bearing wall in a *vomitorium* arch, and expulsion of voussoirs in another arch near the *parascenium* that looked like piano keys shifted (**Figure 15**). We can firmly state that these structural damages were not induced by earthquakes because they occurred after the reconstruction works of this archeological site carried out in the 1980s and without seismic events to justify them. Rather, these

Figure 14.
Ait Kamara, corner failure pulling down the roof slab (grade 4, class A). Source: P Murphy.

Figure 15.
Baelo Claudia, roman ruins (theatre): bowing of a vomitorium *wall (left) and expulsion of voussoirs near the* parascenium *(right), which show a tensile stress in the direction of the slope. Source: J A Aparicio.*

effects can be explained by the instability and slope of the ground, as well as a bad combination between the weight of the structure, the insufficient foundations, and the progressive and slow landslide.

A single shear crack only proves the existence of a one-way displacement force. However, X-shaped cracks are unmistakable signs of lateral and reverse forces that result in a very characteristic diagonal crack pattern. The best candidates are earthquakes due to the effect of S-waves and surface waves, particularly Love waves, which transmit loads in opposite directions. In Al Hoceima, this type of damage is found in any vulnerability class buildings (A, B or C). **Figure 16** shows a very striking case, where the X-shaped damage completely surrounds the load-bearing walls on the ground floor of a four-story residential building of vulnerability class B in Imzourem (grade 3). There are no shear cracks on the upper floors, which is a clear indication

Figure 16.
Imzourem, X-shaped damage completely surrounding the load-bearing walls on the ground floor of a four-story residential building of vulnerability class B (grade 3). Source: P Murphy.

of a soft-story damage, which will be discussed later. X-shaped cracks are sometimes blurred by the loss of outer leaf or toppling of the external walls (**Figure 17**).

The effects of this diagonal tension cracking are also common in infill walls of RC structures where, except in case of collapse, are clearly visible. They spread from lower to upper floors, with a more severe impact on the ground floor after receiving the loads of seismic shaking. In this case, the positive aspect is that these infill walls are not structural elements, unlike in buildings of class A or B, and must be assessed as damage of grade 3 in buildings of vulnerability class C, unless the RC frame structure has been seriously damaged. When X-shaped cracks cross external infill walls located between discontinuities or openings arranged for windows and doors, and the location and depth of these cracks coincide with a RC frame column that ends up being damaged, it can result in a very characteristic type of damage called "short column" or "captive column" (**Figure 18**). This effect is caused by the modification of the expected proportional distribution along the column body of its deformation ability under the influence of lateral loads [20], due to a partial confining of RC frames and a lesser stiffness of a free portion of the column less supported by partitioning brickworks. The consequence is a shorter column that concentrates most of the shear stress, i.e., a major part of the column ductility is lost.

Figure 17.
Examples of X-shaped damage clearly visible in a single-story class A house (above) and blurred by loss of outer leaf in a four-story residential block (below). Source: P Murphy.

Figure 18.
Imzourem, short column effect in a three-story residential block of vulnerability class C (grade 4). On the right, a detail of the damage is shown. Source: P Murphy.

Figure 19.
Alhucemas, soft-story failures: (a) tilting of RC frames on the ground floor; (b) soft-story damage with clear X-shaped crack on the infill wall; (c) collapse of ground floor due to a previous soft-story damage. Source: P Murphy.

5.3 Bad practices in RC frames and soft-story damage

The housing blocks in Al Hoceima were conceived on the basis of a wrong construction pattern very widespread throughout the Ibero-Maghrebian region, with some particularly distinctive features. The partial and total collapse of grade 4 and 5 observed in

RC structures are due to several key defects for the results. The use of non-corrugated steel rods in the vertical and horizontal elements of RC frames is one of the most important errors, because it does not prevent the rebar from sliding inside the concrete core; the longitudinal steel rebars were thick enough to support the weight and height of the structure but not the lateral deformations and bending from additional loads; and the stirrups were not hooked in the correct way to prevent the openning and separation from the steel mesh. Moreover, in the column-beam joints, the stirrups are placed at the same equidistance as in the rest of the column body, not providing the necessary rigidity to prevent it from plastifying when the columns are forced to tilting.

But the most damaging and characteristic construction pattern of the 2004 Al Hoceima earthquake is undoubtedly the soft-story failure. The distribution of the residential buildings was as follows: four or five floors high, densely partitioned in upper flats by interior infill walls embedded between the RC frames and a ground floor less partitioned or completely diaphanous for use as garage in most cases or as small stores. These walls help to stiff the RC frames, reducing the bending of the columns under horizontal displacements of the structure. In areas of moderate to high seismic risk, the upper floors, which are highly rigidized, perform like an unique and solid block that sends all the elastic stress to the ground floor frames. As a consequence, the conections between the column heads on the first floor and the slab on the second floor come under load. If the column-slab joint is not reinforced with the stirrups needed, the column would be excesively bended, producing a type of failure called "plastic hinge" [21]. As a consequence, irreversible tilting of the structure or collapse can occur (**Figure 19a**), transferring the damage in many cases to the upper floors, due to the strong impact during the fall (**Figure 19c**).

6. The Lorca earthquake of May 11, 2011

The epicenter of the Lorca earthquake (Spain) of May 11, 2011, Mw = 5.1 (IGN), was located about 4.5 km from downtown and was preceded by another less violent event of Mw = 4.5, widely felt one hour and 45 minutes before the main shock. The very short distance, shallow depth of the hypocenter (5 km) and geological conditions such as soft soils and, probably, progressive subsidence due to the massive exploitation of aquifers in the Guadalentín Valley, caused or increased a widespread and rough damage not precisely to the most vulnerable structures of class A or B, but to monumental and, mainly, residential buildings of class C which, as in the case of Setúbal, had been replacing traditional construction patterns. Two buildings collapsed and in the following weeks and months almost 1,164 houses and 45 industrial facilities and warehouses had to be demolished, with unrecoverable structural damage. The two collapsed buildings were the church of Santo Domingo (class C, but of low resistance) and a four-story residential block of RC frames (three housing floors and basement for garage), that had been evacuated after the first shaking.

This seismic event in a relatively modern city with a majority presence of RC structures is a powerful evidence that moderate earthquakes of magnitude M<6 can cause a great destruction and that the failure of non-structural elements can also lead to catastrophic consequences. In this case study of seismic behavior of buildings, we will only focus on the effects on class C residential buildings.

6.1 The absence or inadequacy of earthquake-resistant standards

Since the adoption of RC structure as the most widespread construction practice, four earthquake-resistant national standards have been approved in Spain: 1968, 1974, 1995 and 2002. The continuous updating of these legal provisions in a relatively very short period of time shows that the heavy damage caused during the succesive seismic events occurred in this country with intensities ≤VII (**Table 2**), have highlighted the inadequacy of each previous earthquake-resistant standard. All of them have been imposing more rigorous technical requirements and guidelines for the construction of new buildings and major rehabilitation works but have not prevented structures built under the previous rules from being exposed to the risk of collapse or seismic damaging. In addition, the rule currently in effect also do not guarantee the absence of damage to new buildings raised after the effective date of the law and only aims to avoid the immediate collapse of the structures.

Date	Time	Lat.	Long.	Depth (km)	Int.	Mag.	Epicenter
1950/04/04	03:06:22	433.000	−60.000	—	VI	4.6 M_D	Teverga
1950/05/02	07:37:46	381.500	−13.333	—	VI	4.0 M_D	Archena
1950/07/01	12:19:44	371.000	−25.333	—	VI	3.8 M_D	Gergal
1951/03/10	10:38:26	375.950	−39.750	15	VII	5.2 M_D	Castillo de Locubín
1951/05/19	15:54:26	375.670	−39.170	19	VII	5.3 M_D	Castillo de Locubín
1953/09/28	21:41:10	411.333	−15.833	—	VII	4.7 M_D	Used
1954/01/08	16:33:50	369.333	−38.833	—	VII	4.2 M_D	Arenas del Rey
1955/11/27	20:30:08	373.017	−24.583	5	VI	4.1 M_D	Bayarque
1956/04/19	18:38:54	371.917	−36.833	5	VII-VIII	5.0 M_D	Purchil
1956/04/22	15:56:14	372.800	−36.100	5	VI	3.7 M_D	Calicasas
1956/04/29	14:54:29	371.833	−36.833	—	VI	—	Albolote
1956/05/03	01:03:43	373.867	−35.967	5	VI	4.3 M_D	Iznalloz
1956/05/14	09:57:32	371.833	−36.833	—	VI	—	Albolote
1956/06/05	11:41:24	371.717	−70.983	5	VI	4.2 M_D	Punta Umbría
1956/08/16	02:09:40	369.100	−86.067	5	VI	5.0 M_D	Golfo de Cádiz
1958/01/16	15:13:38	381.000	−0.6000	—	VI	—	Guardamar del Segura
1958/02/05	10:18:25	384.583	−0.7350	5	VI	4.7 M_D	Petrer
1958/06/18	14:24:17	389.000	−15.250	10	VI	4.3 M_D	Hoya-Gonzalo
1958/12/22	02:48:16	381.833	−11.167	—	V-VI	4.0 M_D	Fortuna
1959/08/23	22:21:30	355.133	−32.267	20	VI	5.4 M_D	Alborán Sur
1960/06/01	06:18:54	380.967	−0.9117	5	VI	4.4 M_D	Redován
1960/11/14	20:10:26	370.283	−53.283	5	VI	4.5 M_D	Pruna
1960/12/05	21:21:47	356.900	−66.217	5	VII	4.9 M_D	Golfo de Cádiz
1961/02/10	18:52:01	417.250	−61.967	—	VI	5.2 M_D	Zamora
1961/09/03	23:33:13	419.333	−20.833	—	VI-VII	4.6 M_D	Aguilar Río Alhama
1962/05/03	23:27:22	438.850	−70.150	5	VI	4.3 MbLg	Cantábrico

Date	Time	Lat.	Long.	Depth (km)	Int.	Mag.	Epicenter
1963/01/19	20:50:29	382.167	−10.500	—	VI	3.3 MbLg	Abanilla
1964/01/29	01:47:53	370.583	−36.233	5	VI	3.7 MbLg	Dílar
1964/03/15	22:30:26	361.317	−77.500	30	VII	6.2 MbLg	Golfo de Cádiz
1964/06/09	02:33:35	377.367	−25.667	5	VII	4.8 MbLg	Galera
1964/09/09	09:39:45	370.850	−36.200	5	VII	4.3 MbLg	Otura
1967/08/03	00:34:13	383.567	−12.883	5	VI	3.9 MbLg	Jumilla
1969/02/28	02:40:32	359.850	−108.133	20	VIII	7.8 Mw	SW Cape St. Vincent
1970/03/14	15:48:09	424.800	16.800	—	VI	4.3 MbLg	Ílles de Cerdanya
1972/03/16	21:31:32	374.200	−22.450	5	VII	4.8 MbLg	Partaloa
1976/09/26	04:29:20	388.867	−0.5933	5	VI	4.0 MbLg	Aielo de Malferit
1977/06/06	10:49:12	376.450	−17.283	9	VI	4.2 MbLg	Lorca
1979/01/16	00:55:16	428.883	−71.517	80	VI	3.6 MbLg	Becerreá
1979/03/20	21:53:56	371.633	−38.017	5	VI	4.1 MbLg	Chimeneas
1979/06/19	03:55:53	371.483	−35.967	5	VI	3.2 MbLg	Cájar
1979/06/20	00:09:06	372.483	−34.917	60	VI	4.5 MbLg	Beas de Granada
1979/07/30	00:55:25	371.133	−36.733	5	VI	3.7 MbLg	Alhendín
1979/07/31	21:43:20	371.167	−36.033	5	VI	3.9 MbLg	Gójar
1979/11/25	01:56:27	368.650	−37.733	5	VI	3.4 MbLg	Lentegí
1979/12/18	05:47:34	428.883	−71.633	20	VI	4.2 MbLg	Becerreá
1980/11/11	10:59:46	378.333	−52.150	5	VI	4.1 MbLg	Hornachuelos
1988/08/20	13:03:03	372.067	−37.667	2	V-VI	3.9 MbLg	Chauchina
1989/12/20	04:15:05	372.250	−73.917	23	VI	5.0 MbLg	Ayamonte
1991/08/14	10:32:08	387.550	−0.9600	2	VI	4.1 MbLg	Caudete
1993/12/23	14:22:35	367.800	−29.367	8	VI-VII	5.0 MbLg	Berja
1995/11/26	05:39:40	380.383	−12.700	2	V-VI	4.1 MbLg	Alguazas
1995/11/29	23:56:28	428.167	−73.033	9	VI	4.6 MbLg	Triacastela
1995/12/24	14:29:21	428.600	−73.150	15	VI	4.6 MbLg	Baralla
1997/05/21	23:50:45	427.833	−72.583	13	VI	5.1 MbLg	Triacastela
1999/02/02	13:45:17	380.963	−15.014	1	VI	4.7 MbLg	Mula
2005/01/29	07:41:32	378.535	−17.555	11	VII	4.8 Mw	Aledo
2011/05/11	15:05:13	377.196	−17.076	2	VI	4.5 Mw	Lorca
2011/05/11	16:47:26	377.175	−17.114	4	VII	5.1 Mw	Lorca
2016/01/25	04:22:01	356.004	−38.056	12	VI	6.3 Mw	Alborán Sur

Table 2.
Earthquakes felt with intensities VI to VII in Spain between January 1, 1950 and December 31, 2019. Note that earthquakes of magnitude M < 5 can also cause effects of intensity VII in direct relation to the shallowness. Source: Instituto Geográfico Nacional (IGN).

In Lorca, most of the damaged RC housing blocks had been built in three different construction periods: before the first anti-seismic standard of 1968, during the period from 1968 to 2002, and after 2002 standard, in use on the date of this earthquake. But none of these technical rules devoted enough extension to deal with the coupling conditions of non-structural elements, with the consequences that will be discussed below. The first RC housing blocks in Lorca began to be built from the early 1950s onwards, in a period of time marked by the international blockade and economic situation of autarchy (self-production) of the Spanish government after the Second World War. Faced with the impossibility of importing raw materials, steel rebars of low quality and scarce quantity were used for the two essential elements of RC frames: beams and columns. In fact, several patents were developed in Spain to create RC beams containing up to only two steel rebars [22].

However, although it seems difficult to explain, older RC buildings did not suffer a greater damage than those built after the 2002 standard. In **Figure 20** we can appreciate slight shear cracks in the façade of pre-1968 RC buildings, not showing apparent structural damage or deformations of RC frames on the ground floor, despite the lower stiffness due to the lack of infill walls (grade 3, class C). Paradoxically, in **Figure 21** we have the complete collapse of the four-story residential block mentioned above, built during the transition period to the 2002 earthquake-resistant standard. This means that improving rules does not always implies improving resistance.

6.2 The hazard of non-structural elements

The typical design of residential buildings in Lorca is formed by a RC supporting structure (columns and beams) and double-leaf external walls separated by an inner cavity, used as thermal insulation, filled with expanded polystyrene sheets. The internal wall is made of hollow brick, and the external wall of unplastered solid red brick. This external panel was not confined into the RC frame, but externally attached with mortar to the structure, acting rather as cladding or load-bearing wall and not properly as infill wall. In addition, the two brick walls were not tied together with any kind of coupling element, and the lack of plaster, which serves as cohesive mesh and grip for the bricks, provided less resistance to the external face.

The 2011 Lorca earthquake caused nine fatalities due to the fall of these non-structural elements from façades (**Figure 22**) and the evident cause-effect relationship led to a conclusion that became an axiom: non-structural elements also

Figure 20.
Lorca, shear cracks in pre-1968 RC buildings of class C (grade 3). There is apparently no evidence of structural damage, and on the ground floor (left) the columns forming an evident soft story have no sign of tilting. Source: IERD.

Figure 21.
Lorca, complete collapse of RC residential building (grade 5) designed under the earthquake-resistant standard prior to the 2002 standard: (a) the three slabs are completely collapsed without any gap to allow survival; (b) plastic hinges and overturning in the direction of the slope of the street; and (c) plastic hinge in the adjacent building caused during the collapse, wedging against the base of the column. Source: IERD.

kill [23]. This damage took place in several steps: (1) formation of shear cracks in the infill walls caused by cyclic reverse movements of the ground due to seismic shaking; (2) detachment and drift of external walls from RC frames; (3) bending and fall of cladding and external walls. **Figure 23** shows the different types of damage here described: shear cracks cause the detachment and loss of stone or marble cladding and the toppling of the outer leaf of the masonry wall, made in this case with hollow bricks (grade 3, class C). After the collapse of the wall, the expanded polystyrene sheets are exposed outside the inner cavity of insulation. The drift between brick infills, with no connecting elements between them, is also clear. However, there are no shear cracks in the cantilever plaster at the top of the building entrance, which proves the high vulnerability of the infill wall design. The same situation occurs in **Figure 24**, at a moment prior to the external wall detachment, appearing X-shaped cracks by reversal of shear forces.

The lateral loadings were stronger in ground floors, due to the same widespread and wrong conception of structural design exposed in the case of Al Hoceima: the soft story effect. In this construction pattern, the upper floors are more partitioned for residential use than the ground floor, commonly used for open-plan commercial premises, garage, or other purposes. Given this so unbalanced stiffness distribution, the building performs like a rigid block that swings over RC frames of the ground floor, resulting in shear cracks, corner failure, X-shaped or diagonal cracks, partial or complete overturning of infill walls or, in the worst case, plastic hinges that do involve structural damage.

Figure 22.
Lorca, debris fallen on vehicles and sidewalk. The center of the street is free of danger. In Lorca, people died while walking or looking for protection near the façades. Source: IERD.

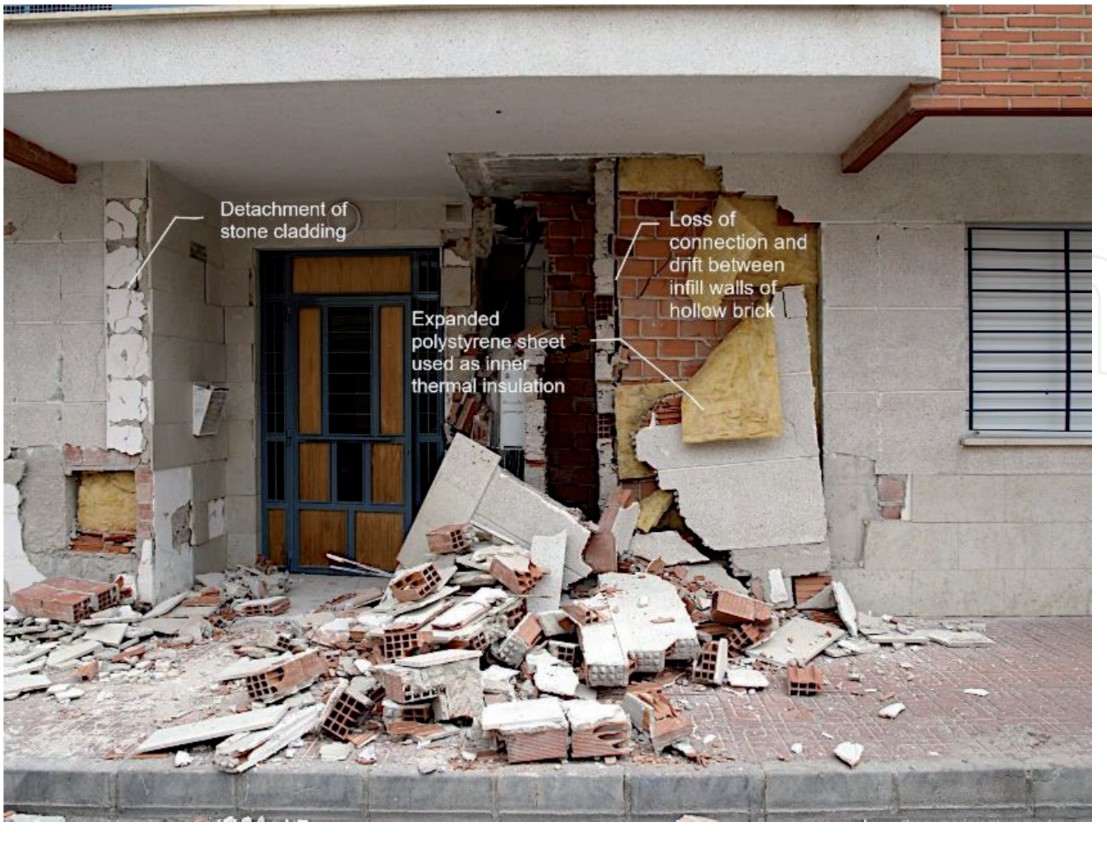

Figure 23.
Lorca, shear cracks caused the detachment and loss of stone cladding and the toppling of the outer leaf of the brickwork wall (grade 3, class C). Source: IERD.

Figure 24.
Lorca, loss of stone cladding, fall of window lintel and X-shaped crack on external wall about to fall down. Source: IERD.

6.3 Miscalculations lead to catastrophic results

The only collapsed building in Lorca was designed under the earthquake-resistant standard of 1995. Following the technical requirements of this regulation, the RC frames, columns and beams, were reinforced by four longitudinal steel bars enclosed by vertical stirrups placed at regular intervals, including the column-beam or column-slab joints. In addition, the stirrup ends were bent at 90°, without forming a hook around the longitudinal rebars. In **Figure 25a–c**, each RC column is made up of four longitudinal steel rebars and stirrups with 90° hooks (**Figure 25d**). The 1994 earthquake-resistant standard required four rebars per column in areas with expected gravity acceleration values <0.16 g and eight rebars per column in areas with acceleration ≥0.16 g (m/s^2). The maximum estimated value for the municipality of Lorca was 0.12 g; therefore, the collapsed building studied here, built in 2001, fulfilled the construction requirements at the time. Afterwards, the 2002 standard reduced to 0.12 g the acceleration value needed to force the implementation of eight rebars per column, but it was too late. Obviously, this building ——and many others of similar design—— had used inadequate construction parameters that were to be approved the following year, stablishing stricter technical requirements more consequent with the behavior of RC frames under acceleration values ≥0.12 g.

As said above, the effective acceleration value was 0.37 g, that is, three times higher than the value for which the structure had been engineered. With this level of vulnerability, these RC structures, with four rebars per column arranged for maximum accelerations of 0.12 g, would hardly have been able to withstand the effective accelerations of 0.37 g without suffering severe damage. The design miscalculation of RC frames was 2/3 lower than the real value. If initial calculations had been overestimated, the damage would have been considerably reduced; but reinforcing structures with steel material means a significant increase in construction costs.

Several photographs taken in the affected area show the difficulty of the RC frames in other residential buildings to resist the violence of the horizontal

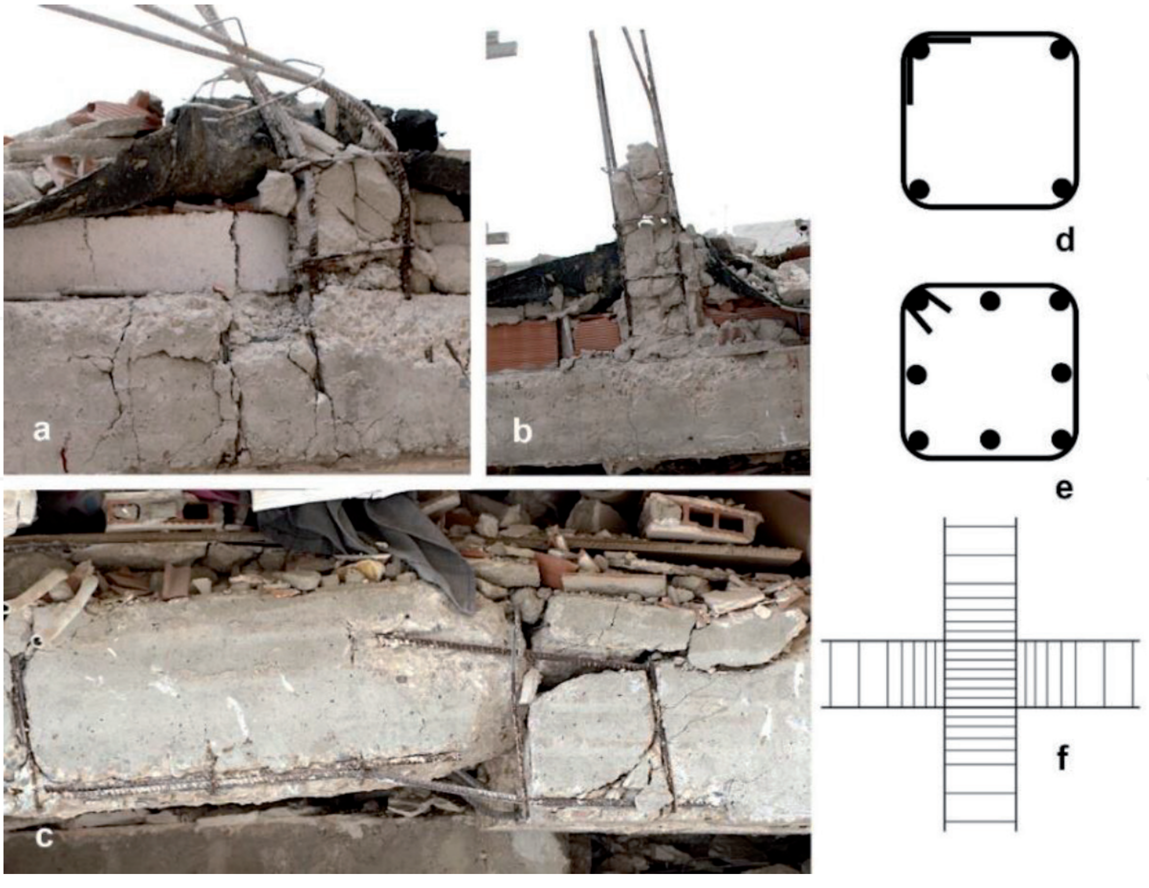

Figure 25.
Lorca, details of the RC residential block collapsed in Lorca, showing the four-rebar cores of beams and columns: (a) and (b) show the regular equidistance between the stirrups near the column-beam joints; (c) beam with similar arrangement of rebars; (d) drawing of the four-rebar longitudinal distribution used in this building with stirrup ends bent at 90°; (e) more adequate design for seismic resistance, with eight rebars and stirrup bent at 135°; (f) correct way to reinforce the RC column-beam joints. Source: IERD.

forces. As an example of better structural behavior, in **Figure 26** we can observe a complete damage in a double-leaf infill wall in a housing block with overturning of internal and external faces, but without apparent cracks in the RC frame and with no signs of plastic hinges or deformation in the column-beam joint (grade 3, class C). On the contrary, in **Figure 27** the loss of cladding allows us to clearly appreciate the occurrence of shear cracks at the base of the column-beam connection of the second floor, implying in all cases a moderate structural damage. It is due to the much more stiffness of the slab, which overloads the column resistance by sending all the energy of horizontal forces to the column base, not reinforced with an adequate seismic-resistant design. This damage, although less frequently, is not exclusive to the column-beam or column-slabs joints and can also occur in the middle body of the column (**Figure 28**), especially in case of short-column effect.

The damage to the column-beam joints of RC frames is consequence of the lack of steel reinforcement at the coupling node. As shown in **Figure 25**, the stirrups have a regular equidistance along the column as in the beam-column joints; as a result, the RC structure plastifies. A greater number of stirrups in the coupling node, progressively reducing the distance between them towards the intersection core, would increase the structure resistance and distribute the displacement energy along the full length of the columns, not transferring all the cyclic reversal of loads to the column-beam joints (**Figure 25f**). In addition, in areas with a moderate to high level of seismicity the stirrups should be anchored to the longitudinal rebars, overlapping 135° hooks [24] to avoid the opening of the closed-loop and outward bending of the rebars (**Figure 25e**). The Turkish Earthquake Code 2007 and Indian Standard IS13920-1993 are two examples of the implementation of these earthquake-resistant requirements.

Figure 26.
Lorca, complete overturning of double-leaf wall with overturning of both brickwork faces, but without apparent cracks in the RC frame. Source: IERD.

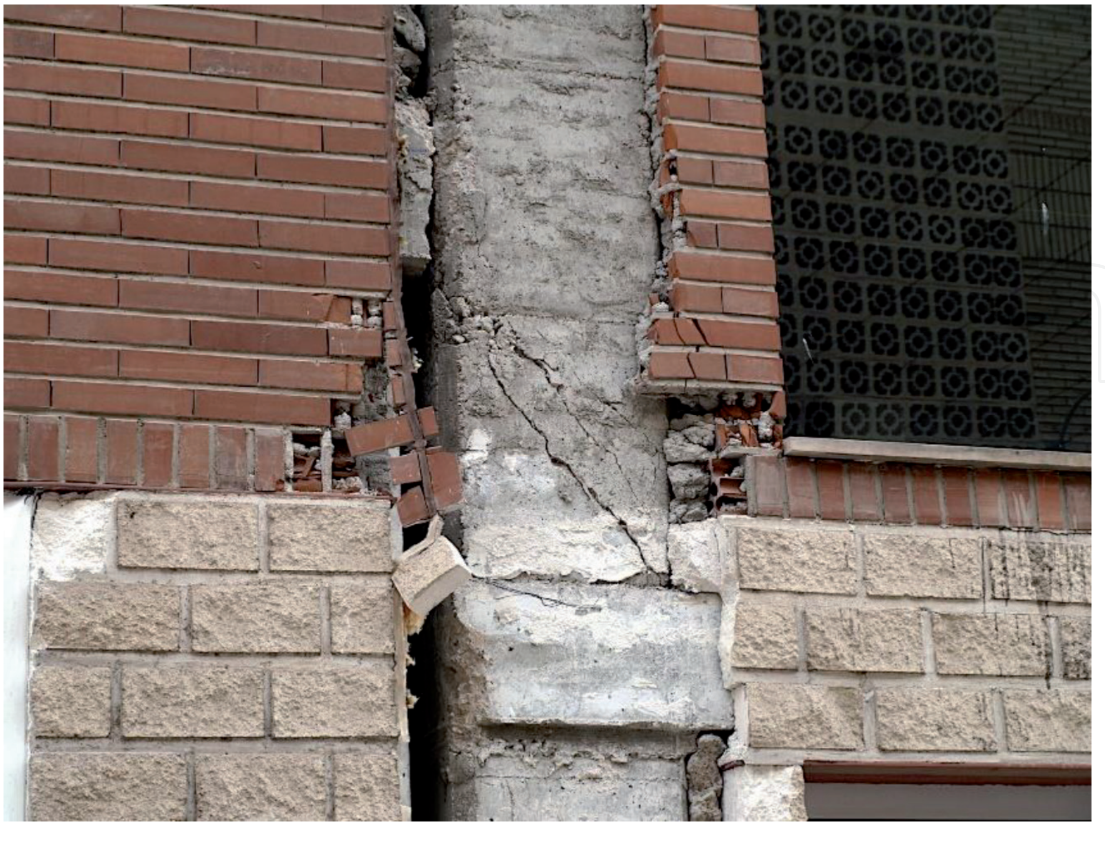

Figure 27.
Lorca, cracks in the column-beam base suggest the incipient formation of a plastic hinge. The loss of cladding is due to a hammering effect with the adjacent building. Source: IERD.

Figure 28.
Lorca, X-shaped cracks in infill walls and loss of concrete in the middle body of the RC column suggest a soft story effect. Source: IERD.

7. Conclusions

After the occurrence of earthquakes it is necessary to carry out a detailed field report, taking all the detailed photographs possible, to document and analyze the behavior and vulnerability of buildings according to the magnitude, distance and depth of the seismic event, in relation to the construction techniques used in the past and the adequacy of the current construction standards. The reconstruction of a territory severely affected by earthquakes cannot be planned using the same wrong techniques or with the standards in force that have demonstrated its inadequacy. Otherwise, a future earthquake with identical or higher parameters will again cause the same level of destruction.

For a resilient and sustainable reconstruction of devastated areas, a thorough review of the earthquake-resistant building standards and construction requirements is needed, aiming to ensure the resistance of structures to the higher stresses expected in the macroseismic area. A more precise seismic microzonation for smaller sectors is also required to get accurate structural strength calculations; the case of Lorca studied in this chapter shows that within the same city considered as a whole within the same level of seismic acceleration, specific points can undergo much greater accelerations, probably due to geological anomalies or discontinuities of the ground. Lessons learned like the ones we have discussed in this chapter should help to avoid repeating the same errors in other places. For this reason, it will be necessary to rethink whether the current construction patterns are a good example of good practices, whether they require a modification or reinforcement of the structural design, or whether they should be changed by other patterns more consistent with seismic activity in the area. It is also very important to note that the increase in costs of implementing earthquake-resistant systems in buildings will normally be much less than the volume of economic losses caused by earthquake damage.

It is evident that the buildings designed under previous or obsolete constructive standards will continue to be vulnerable even when reinforcement works are carried out, so it would be a good preventive task to carry out or review the seismic vulnerability maps, identifying the construction patterns used in each point of the map, their level of vulnerability and types of possible damage here described. It is also very important that the population be aware of the behavior of each type of structure in each city or neighborhood where they live, and customize the recommendations to the public on how they should respond during and after an earthquake at each time and place. Finally, it should be said that no country is exempt from being affected by a seismic disaster and therefore we must continue making efforts to increase the buildings resistance. Because inadequate construction patterns can be repeated and many buildings are exposed to the risk of collapse in very large geographic areas that can encompass several countries, it would be a great opportunity to improve earthquake-resistant designs by applying the goals of the 2030 Agenda, especially the goal 11 "cities", to significantly reduce the number of deaths and people affected, and substantially decrease the direct economic losses caused by disasters.

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Nomenclature

ERD	Earthquake-resistant design
IERD	Instituto Español para la Reducción de los Desastres
IGN	Instituto Geográfico Nacional
IPMA	Instituto Português do Mar e da Atmosfera

Author details

José Antonio Aparicio Florido
Instituto Español para la Reducción de los Desastres (IERD), San Fernando, Cádiz, Spain

*Address all correspondence to: apariciofloridoi@gmail.com

References

[1] Buforn E, Sanz de Galdeano C, Udías A. Seismotectonics of the Ibero-Maghrebian region. Tectonophysics. 1995;248:247-261. SSDI: 0040-1951(94)00276-2

[2] Bezzeghoud M, Ayadi A, Caldeira B, Fontiela J, Borges J F. The largest earthquakes in Algeria in the modern period: the El Asnam and Zemmouri-Boumerdès faults. Física de la Tierra. 2017;29:183-202. DOI: https://doi.org/10.5209/FITE.57618

[3] Aparicio JA. 1755: El maremoto que viene. Cádiz: Q-book; 2017. 251 p 978-84-15744-50-4

[4] Grandin R, Borges JF, Bezzeghoud M, Caldeira B, Carrilho F. Simulations of strong ground motion in SW Iberia for the 1969 February 28 (Ms = 8.0) and the 1755 November 1 (M ~ 8.5) earthquakes - II. Strong ground motion simulations. Geophysical Journal International. 2007;**171**:807-822. DOI: 10.1111/j.1365-246X.2007.03571.x

[5] Baptista MA, Miranda PMA, Victor LM. Maximum entropy analysis of Portuguese tsunami data: the tsunamis of 28.02.1969 and 26.05.1975. Science of Tsunami Hazards. 1992;**10**: 9-20 ISSN: 0736-5306

[6] Martínez Solares JM. Tsunamis en el contexto de la Península Ibérica y del Mediterráneo. Enseñanzas de las Ciencias de la Tierra. 2005;**13**(1):52-59 ISSN: 1132-9157

[7] Paradise TR. Perception of seismic risk in a Muslim city. The Journal of North African Studies. 2006;**11**(3):243-262. DOI: 10.1080=13629380600802961

[8] Grünthal G, editor. European Macroseismic Scale 1998. Luxembourg: Centre Européen de Géodynamique et de Séismologie; 1998. 99 p 2-87977-008-4

[9] Trêpa MV. Relatório do inquérito levado a cabo nas provincias de Estremadura, Alto Alentejo, Baixo Alentejo e Algarve sobre o sismo de 28 de fevereiro de 1969. Serviço Meteorológico Nacional: Portugal; 1969 41 p

[10] Murphy P. Al-Hoceima earthquake on February 24, 2004. 2004. Available from: https://www.emsc-csem.org/Files/news/Earthquakes_reports/Alhucemas_040224_eng.pdf [Accessed: 2020/09/05]

[11] Aparicio J A, Peláez A, Peláez A E. El terremoto de Lorca del 11 de mayo de 2011. 2011. Available from: http://ierd.es/wp-content/uploads/2014/06/informeIERD-terremoto-lorca-11052011.pdf [Accessed: 2020/09/05]

[12] Aparicio JA. Effects of the 28 February 1969 Cape Saint Vincent Earthquake on Ships. Pure and Applied Geophysics. 2020;**177**:1801-1808. DOI: 10.1007/s00024-019-02368-0

[13] Borges JF, Bezzeghoud M, Caldeira B, Carvalho J. Ground-Motion Simulation in the Lower Tagus Valley Basin. Pure and Applied Geophysics. 2015;**172**:2411-2420. DOI: 10.1007/s00024-015-1060-7

[14] Carvalho J, Dias R, Pinto C, Leote J, Mendes-Victor L. A soil classification for seismic hazard assessment and mitigation of the Algarve. The 14th World Conference on Earthquake Engineering (WCEE '08). 12-17 October 2008; Beijing, China.

[15] Teixeira C. Alguns aspectos geológicos dos efeitos do sismo de 28 de fevereiro de 1969. Boletim da Sociedade Geológica de Portugal. 1975;**XIX**(III):239-250

[16] Paula A, Sousa C. Evaluation of 1947-1993 macroseismic information in

Portugal using the EMS-92 scale. Annali di Geofisica. 1996;**XXXIX**(5):989-1003. DOI: 10.4401/ag-4029

[17] Mendes AS. Notícia acerca do sismo de 28 de Fevereiro de 1969 em Portugal Continental. Finisterra. 1969;**IV**(8):273-277

[18] Miranda J M, Carrilho F. 45 anos do sismo de 28 de fevereiro de 1969. Instituto Português do Mar e da Atmosfera. 2014.

[19] Buforn E, López-Sánchez C, Lozano L, Martínez-Solares JM, Cesca S, Oliveira C, et al. Re-evaluation of seismic intensities and relocation of 1969 Saint Vincent Cape seismic sequence: a comparison with the 1755 Lisbon earthquake. Pure and Applied Geophysics. 2020;**177**:1781-1800. DOI: 10.1007/s00024-019-02336-8

[20] Guevara LT, García LE. The captive- and short-column effects. Earthquake Spectra. 2005;**21**(1):141-160 ISSN: 8755-2930

[21] Guney D, Aydin E. The nonlinear effect of infill walls stiffness to prevent soft story collapse of RC structures. The Open Construction and Building Technology Journal. 2012;**6**:74-80. DOI: 10.2174/1874836801206010074

[22] Aparicio J A. 1947 Cádiz, la gran explosión. 1st ed. Cádiz: Cazador de Ratas;2017. 528 p. ISBN: 978-84-945867-5-0

[23] Murphy P. Terremoto de Lorca 11 mayo 2011. In: 4th National Congress of Seismic Engineering; 18-20 May 2011; Granada.

[24] Susanto A, Kasyanto H, Susilahadi S. Experimental study of 90° hook and standard hook at the end of reinforced concrete beam stirrup. IOP Conference Series: Materials Science and Engineering. 2020;**830**(2). DOI: 10.1088/1757-899X/830/2/022072