Seismic vulnerability and expected damage in "Ground Zero Area" in El Cabanyal (Valencia)

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The seismic vulnerability assessment of buildings in historic city centres is the first step to mitigate the possible damage, to prevent heritage losses and to preserve their historical identity. In this paper the analysis is focused on the residential buildings of “Ground zero Area” in El Cabanyal. This unique quarter of Valencia, once a fishermen’s settlement, has a strong village-like identity and heritage value. Swallowed up by an expanding city centre and threatened by a poor redevelopment plan, which caused its degradation, its rehabilitation is nowadays the object of a new protection plan.

The seismic vulnerability of the residential buildings has been assessed using the Vulnerability Index Method, obtaining a global damage index, and the equivalent built area expected to be destroyed. Results, implemented in a GIS environment, revealed that, due to the high vulnerability, many of the analysed listed buildings will be significantly damaged. A new detailed analysis is recommended, to define intervention and retrofitting criteria to improve their seismic response, preserving the architectural heritage and defending the unique identity of El Cabanyal.

Keywords: Seismic vulnerability assessment, Vulnerability index method, earthquake damage scenarios, urban areas, Cabanyal Ground Zero area; Valencia

Introduction

Valencia is located in an area of low to moderate seismic hazard. Despite of this, according to previous studies driven by the authors (Guardiola-Víllora and Basset-Salom 2015), the seismic risk is high in the historical districts, because of the vulnerability of the residential buildings, especially those built before the approval of the first Spanish Seismic Code (PGS-1 1968).

This research focuses on the seismic vulnerability assessment of the residential buildings in Ground Zero Area in El Cabanyal (Valencia). El Cabanyal is one of the old fishermen quarters which was annexed to the city of Valencia in 1897. The majority of the residential buildings in this historical neighbourhood correspond to unreinforced masonry typologies built mainly from 1900 to 1940. From the experience of the authors in other areas of the city, a great part of the building stock does not meet the necessary requirements to withstand seismic actions and its design ignores other factors which are relevant for an adequate seismic performance.

In 1993 El Cabanyal was declared an Asset of Cultural Interest (BIC) for its architectural, urban, environmental and historical values. Notwithstanding the mandatory protection of the area, the Special Protection and Rehabilitation Plan drafted in 2001 (Plan Especial de Protección y Reforma Interior del Cabanyal-Canyamelar, PEPRI 2001) included the connection of the neighbourhood with the city with a big avenue, destroying a big part of the protected houses and the historic street pattern. After many years of appeals and movements in favour and against this project, with suspension of building permits and demolitions, the area started a progressive process of abandonment, decay and degradation in such magnitude that nowadays it is known as “Cabanyal’s Ground Zero Area”. Fortunately, in 2015, PEPRI 2001 was repealed, and a new plan was drafted, the Special Protection Plan of El Cabanyal (Plan Especial de

Protección del Cabanyal-Canyamelar, hereinafter PEC), which at the time of writing this paper, is in process of approval.

Several European funds have been allocated for building renovation, rehabilitation and retrofitting of the Ground Zero Area, preventing the demolition of the listed buildings. Consequently, assuming that a new period of interventions of different types will take place in the district, this is an opportunity to assess the vulnerability of the residential buildings and obtain the expected degree of damage in case of occurrence of a given earthquake, with the aim of improving their seismic performance and to preserve the cultural value of the historical heritage.

The seismic vulnerability of the building stock has been assessed, using the Risk-UE Vulnerability Index Method (Milutinovic and Trendafiloski 2003, Mouroux et al. 2004), defining the seismic quality of the buildings with a vulnerability index. This index depends on the structural typology and the specific characteristics of each building that might influence its seismic response.

The information has been obtained from different sources such as the Cadastral database, the Municipal Historic Archive of Valencia, the preliminary documents of the PEC and from a comprehensive onsite survey carried out with this purpose. All the collected data have been organised in a database and connected with a Geographical Information System (GIS) to identify each building within the urban context.

Finally, after defining the seismic scenarios (deterministic and probabilistic), the damage probability matrices have been obtained as well as the expected destroyed built area, in order to highlight the relevance of the heritage-possible losses and the importance of improving the performance of the residential buildings.

El Cabanyal neighbourhood

The origin of this historic settlement is set in the XIII century, after the arrival of James I the Conqueror, King of Aragon, to Valencia in 1238. After the capitulation, James I distributed the land among the soldiers and sailors who helped him in the conquest. The book "El llibre del Repartiment de València" (XIII century land registry book preserved in the Crown of Aragon’s Archive) keeps record of the properties donated to five hundred sailors, establishing the origin of two fishermen's quarters, one of them the future Cabanyal neighborhood (Pastor Vila 2012).

Since the beginning, the settlement was organized in a characteristic layout with all the streets on a grid pattern, main streets and façades parallel to the waterfront giving shape to the housing blocks, with east to west oriented thatched fishermen's cabins.

Throughout the XIX century, the area grew parallel to the seashore, becoming a popular zone for rest and leisure. Around the turn of the XX century, the prosperous Valencian bourgeoisie replaced the old thatched huts by elegant townhouses built in different styles, predominantly art-nouveau but also baroque or eclecticism, covering most of the new facades with brightly coloured tiles, making the neighborhood unique. Figure 1 includes pictures of different residential buildings to show the value of the historic neighbourhood and the diversity of architectural styles and periods.

Figure 1. Residential buildings in El Cabanyal (credit: the authors)

With the expansion of the City of Valencia after the demolition of the walls in 1865, several projects proposed the idea of opening a big avenue to connect the city centre with the beach, being one example the 1899 proposal of Casimiro Meseguer (Hervás 2017), shown in Figure 2. None of these projects took place due to economic factors and to the outbreak of the Spanish Civil War in July 1936.

After the end of the war, new urban plans were drafted (1943, 1946). The specific urban plan for El Cabanyal, "Plan Parcial 13" (PP13) reintroduced, in 1953, the proposal to extend the avenue through the quarter, but it wasn't approved at that time.

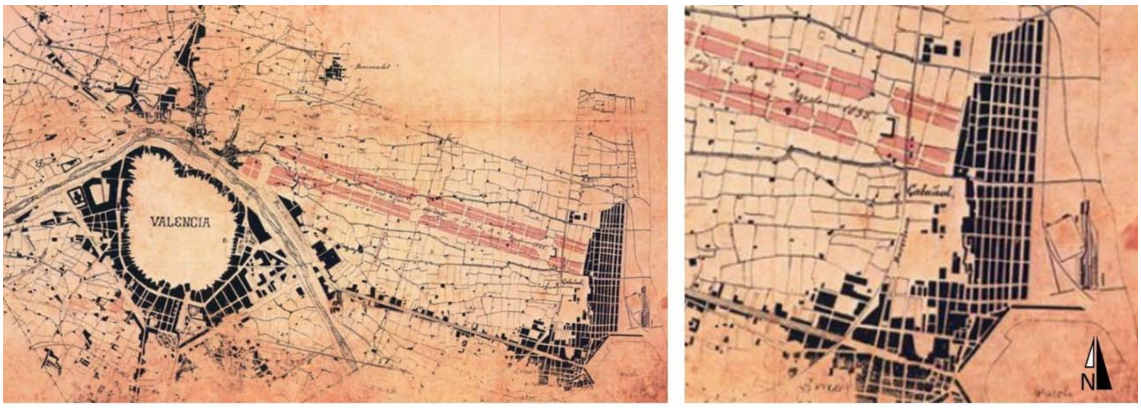

Figure 2. Map of the city of Valencia in 1899, by José Manuel Cortina Pérez with the proposal of Casimiro Meseguer (Llopis, Perdigón, and Taberner 2004)

After the 1957 flood, the "Plan General de Valencia" (1966) was drafted, and the corresponding PP13 approved in 1975. This plan was the starting point of the typological and environmental degradation of El Cabanyal allowing unusual typologies in the area as well as an increase in the buildability and the number of storeys.

The recurring topic of the connexion of the city with the sea continued unsolved after the end of dictatorship when democracy arrived. The controversy of extending the avenue through the quarter and its preservation has remained until the XXI century.

Three years after the approval of PP13 (1978) a resolution of the General Directorate of Artistic Heritage, Archives and Museums of the Ministry of Culture declared six zones in Valencia as Historical Artistic Sites, being El Cabanyal one of them, and in January 1982, the Supreme Court stopped definitely the PP13.

On December 28th, 1988, a new General Urban Plan for Valencia (Plan General de Ordenación Urbana de Valencia, PGOU88) was approved, stating that the area, recognise as Historical Artistic site, should be object of a specific planning which will focus on its regeneration and revitalisation preserving building typologies and street patterns, solving also the access from the city centre. Figure 3a corresponds to the catalogue of the buildings listed by PGOU88 with a protection status (grade 2: or 3[1]).

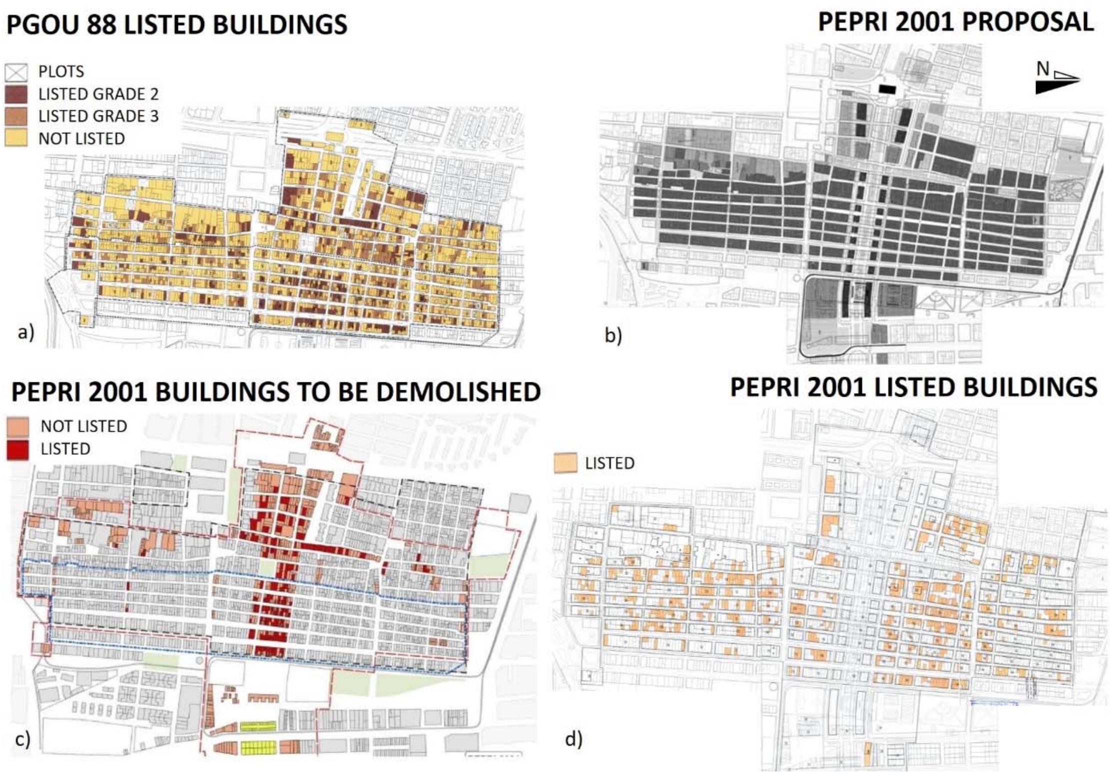

Figure 3. a) PGOU88. Catalogue of listed buildings. b) PEPRI 2001-Proposal, c) PEPRI 2001: buildings to be demolished. d) PEPRI 2001: listed buildings (Source a, d: Valencia City Council, b, c: Herrero García 2016)

In 1993, the original core of the expansion of El Cabanyal was declared an Asset of Cultural Interest (BIC), by a decree of the Valencian Government, acknowledging its heritage value, because of its unique urban layout and built environment. However, despite the BIC declaration, the local government started drafting a special plan in 1998 which was approved in 2001, PEPRI 2001, This plan established the extension of Blasco Ibáñez avenue (formerly Paseo de Valencia al Mar) to the sea crossing El Cabanyal (Figure 3b) and splitting it into 2 halves, tearing the grid pattern of the historical Artistic Site and destroying about 500 buildings (Hervás 2017), many of them

[1] Buildings with a protection grade 2 have an historic or cultural value. All the elements that define their architectural structure and layout (such as main and rear facades, roofing, entrance hall and stairs) must be preserved. Buildings with a protection grade 3 have an environmental value. Their façades and volume must be preserved

listed in the PGOU88 (Figure 3c). The number of buildings listed by PEPRI 2001 (Figure 3d) was reduced drastically, excluding the ones affected by the new avenue.

According to the 1998 Law of Valencian-Cultural Heritage the project of extending the Avenue Blasco Ibáñez planned in the PEPRI 2001, clearly contravened culture and legislation but above all the will and way of life of the inhabitants.

From the approval of this plan, a series of judicial appeals came about, with Court failing sometimes in favour of the neighbours and others in favour of the local City Council. In the meantime, the strategy of the City Council consisted in creating public corporations to buy the buildings to be demolished according to the plan, and then, left them abandoned contributing to its decline and its occupation by drug dealers, and squatters. Soon the affected area was dramatically degraded and, as previously mentioned, began to be known as Cabanyal's Ground Zero Area.

Disregarding law courts prevention about carrying out this plan in a protected area, in 2004, the local and regional government modified the regional Law of Valencian-Cultural Heritage to allow the demolition of these buildings. Later on, in 2009 the Ministry of Culture suspended the implementation of the PEPRI 2001 until being adapted to guarantee the protection of the Historic artistic Site. Nevertheless, in April 2010, the city council started the demolition of the houses affected by the plan. Although the Court finally prevented this action, about 125 houses were demolished, including 28 with the characteristic and unique tiled style (Tarín 2013).

After the local elections in 2015, the new city council repealed the PEPRI 2001 (2016) starting the process of drafting the PEC with the main objective of protecting the entire urban area and recovering the affected zone through repair, rehabilitation and reconstruction. The revised version of this plan was exposed for public information in January 2019 not being approved yet. This new situation triggered the real estate activity of the neighbourhood, being a great opportunity to intervene in the building stock in order to improve their seismic vulnerability.

Description of Cabanyal's Ground Zero Area

This research is focused on the so-called Ground Zero Area in El Cabanyal. Its boundaries (in red Figure 4) have been established including the blocks affected by the extension of the avenue defined in the repealed plan PEPRI 2001 whose implementation led to abandonment and, subsequently, to degradation and decay.

Upon approval of the PEC, these buildings will be rehabilitated considering not only heritage preservation theories but also structural safety and energy efficiency.

It is worth noting that, within Ground Zero Area, a considerable number of buildings are totally or partially owned by the city council or a public corporation. The percentage of these buildings and the tenure status identified by the PEC are depicted in Figure 4. This fact can be considered a guaranty of intervention, rehabilitation and compliance with the structural safety requirements, in short, an opportunity to respect the protected heritage never seen in this community before.

According to the cadastral data base, the analysed blocks include 696 registries from which 75% are residential buildings, 16% are empty plots or completely ruined buildings and the rest (only 9%) correspond, among others, to warehouses or commercial buildings. The state of preservation of the building stock considered in the PEC has been taken as a preliminary information and checked during the on-site survey which was carried out by the researchers. In this area, apart from the abovementioned ruined buildings or empty plots due to demolition, there are a lot of residential buildings with a bad state of maintenance. Some examples can be seen in Figure 5. Unfortunately, many of the ruined buildings were listed in the PGOU88.

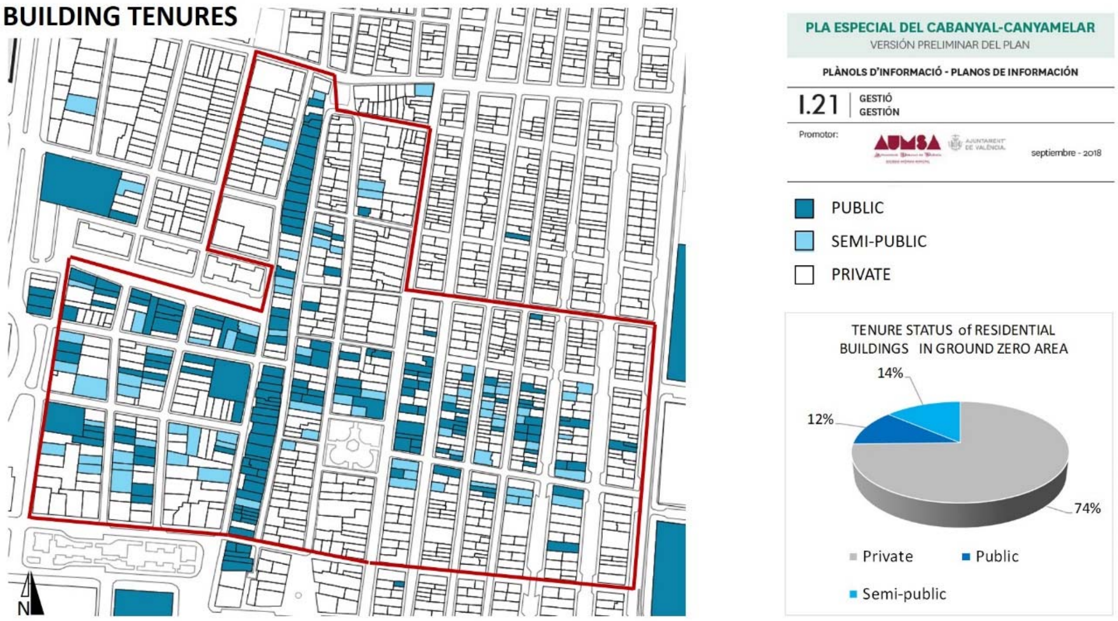

Figure 4. PEC, 2019. Information Plan: tenure status (Source: Valencia City Council)

Figure 5. Example of residential buildings in Ground Zero Area with a bad state of maintenance, ruined buildings and empty plots (credit: the authors)

The age of each residential building in Ground Zero Area has been retrieved from the cadastral database. Most of them were built before the Spanish Civil War (Pastor Vila 2012). New buildings were erected during the sixties and seventies, a period of economic growth and prosperity characterised by a boom in housing construction. Some of these buildings kept the original plots while others combined two or more adjacent plots, increasing, in all cases, the number of storeys up to five or six and in a few cases even up to nine.

Buildings have been classified in periods (Figure 6a) according to their constructive and structural characteristics with regards to their seismic response. These periods will be justified in the next section. The oldest residential buildings standing up were built between 1900 and 1940. They are in total 375 (172 date from 1900-1920, with a relevant number of modernist houses, and 203 from 1920-1940), representing 72.1% of the analysed building stock. It is important to stress that, since then, the number of buildings in each period decreased steadily, with only 12 buildings in the last two periods, due to the suspension of building permits derived from the urban planning and the different judicial appeals, as explained.

Considering the number of storeys, as shown in the bar chart of Figure 6b, more than half of the residential buildings are low rise with two storeys (304 buildings, 58.5%), with only nine buildings exceeding six storeys (1.8%).

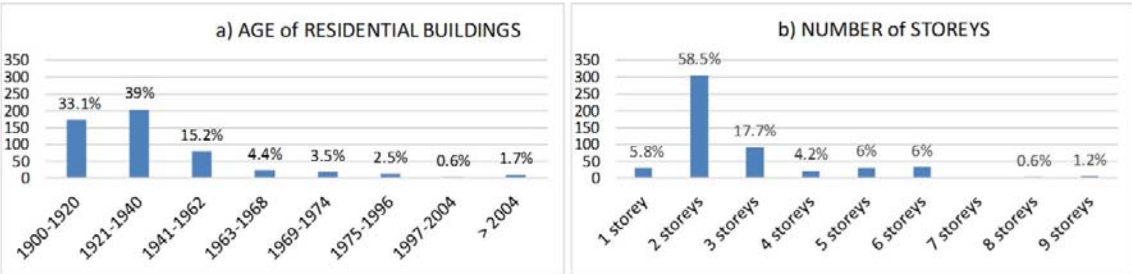

Figure 6. Residential buildings: a) Age b) Number of storeys (Source: Cadastral database)

The prevailing structural system in Ground Zero Area, representing about 77 % of residential buildings, corresponds to unreinforced masonry (URM) load-bearing brick walls with one-way floors with timber or steel beams and joists with lightweight brick vaults infills (Figure 7 a and b). Of the remaining residential buildings, 22% have reinforced concrete (RC) framed structures with mostly one-way concrete joists floors (Figure 7 c) and only 1% have a steel framed structure with masonry infill walls. An example of buildings with different structural typologies can be seen in the original projects retrieved from the Municipal Historical Archive of Valencia (Figure 7: d) URM with timber one-way floors, e) URM with steel one-way floors, f) RC framed structure).

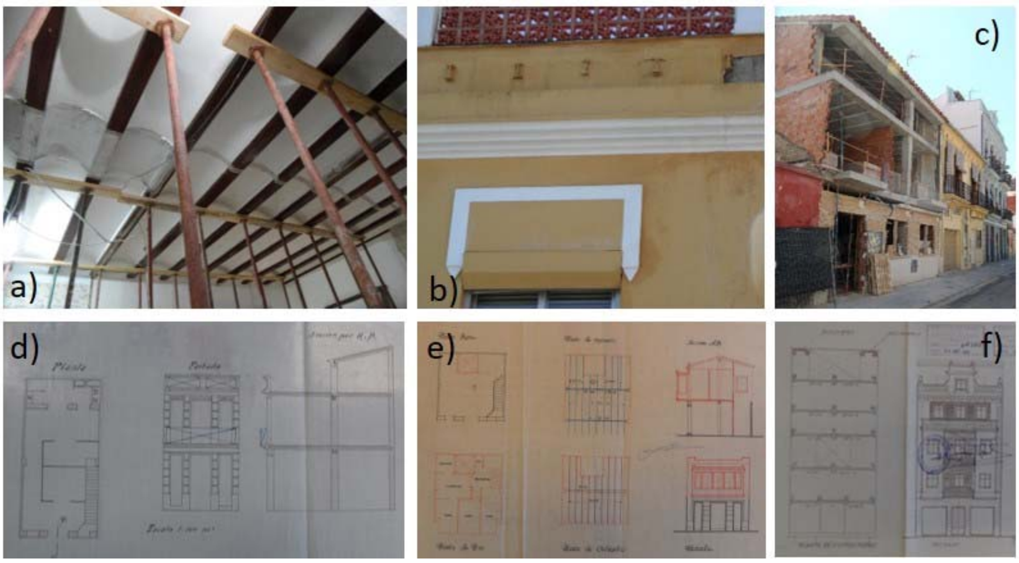

Figure 7. Structural typologies: a) URM timber floors, b) URM steel floors, c) RC framed structure (credit: the authors). Original plans of structural typologies d) URM timber floors, e) URM steel floors; f) RC framed structure (Source: Municipal Historical Archive of Valencia)

The structural typologies in Ground Zero Area correspond to M 3.1 (URM bearing walls with floors made with timber joists and brick vaults), M 3.3 (URM bearing walls with floors made with steel joists and brick vaults), RC1 (RC moment frames), RC3.2 (RC irregular frames with masonry infill walls) and S3 (Steel frame with masonry infill walls), according to the Building Typology matrix (BTM) proposed by Risk-UE (Milutinovic and Trendafiloski 2003). The distribution of the structural typologies in total and itemised in relation with the age (built period) and the number of storeys is shown in Figure 8.

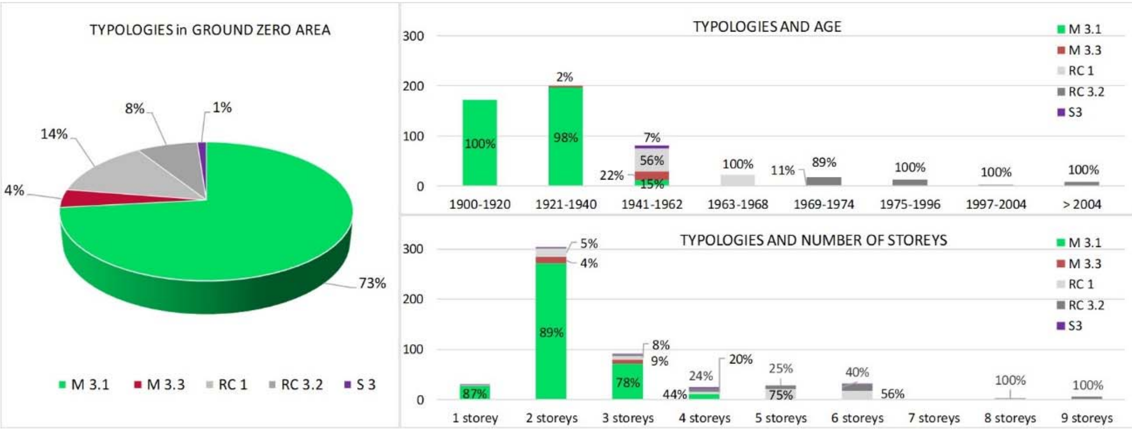

Figure 8. Distribution of the structural typologies in Ground Zero Area: in total, by age (built period) and number of storeys.

Seismic vulnerability assessment

The seismic vulnerability of a structure can be defined as its susceptibility to suffer a certain degree of damage in case of occurrence of a seismic event of a given intensity. Different approaches can be performed to assess the seismic vulnerability of buildings (Calvi et al. 2006; Barbat et al. 2010; Novelli 2017): empirical methods such as the Damage Probability Matrix (Whitman et al. 1973; Dolce et al. 2003) or the Vulnerability Index Methods (Benedetti and Petrini 1984; Giovinazzi and Lagomarsino 2002); analytical methods (D'Ayala and Speranza 2002; Barbat, Pujades, and Lantada 2008; Irizarry et al 2011; Lamego et al. 2017) and hybrid methods (Kappos et al. 2006; Maio et al. 2016; Ferreira, Maio, and Vicente 2017)

The seismic vulnerability of the residential buildings in Ground Zero Area has been assessed with the Vulnerability Index Method (VIM), level 1 (Milutinovic and Trendafiloski 2003), developed under the framework of the European research project Risk-UE (Mouroux et al. 2004), suitable for urban areas where estimates of the seismic intensity and building stock information are available (Chever 2012; Novelli 2017). Several studies have been carried out in Spain with this method, namely in Barcelona (Lantada 2007; Lantada et al. 2010; Lantada, Pujades, and Barbat 2018), Gerona (Irizarry et al. 2012), Granada (Feriche 2012), Valencia (Guardiola-Víllora and Basset-Salom 2015) and Lorca (Feriche et al. 2012; Martínez-Cuevas and Gaspar-Escribano 2016; Ródenas, Tomás, and García-Ayllón 2018).

Risk-UE level 1 Vulnerability Index Method assigns, to each building structural typology, the most probable vulnerability index VI*, the endpoints of the plausible interval [VI-; VI+] and the lower and upper bounds of the possible values [VImin; VImax] (Giovinazzi and Lagomarsino 2004). The Vulnerability Indices corresponding to the residential building typologies in Ground Zero Area are shown in Table 1 (Milutinovic and Trendafiloski 2003).

The particularities of each individual building affecting its seismic performance are taken into account by adding to the representative value (V_I*) a regional vulnerability factor (VR) and a set of behaviour modifiers (Vm). Hence the final value of the vulnerability index, V_I, (higher values corresponding to the highly vulnerable buildings) is obtained as follows:

$$V_I = V_I^* + VR + \sum Vm \quad (1)$$

Table 1 Vulnerability Indices for the residential building typologies in Ground Zero Area (Milutinovic and Trendafiloski 2003)

Typology	V_I^{min}	V_I-	V_I^*	V_I+	V_I^{max}
M3.1	0.460	0.650	0.740	0.830	1.020
M3.3	0.460	0.527	0.704	0.830	1.020
RC1	-0.020	0.047	0.442	0.800	1.020
RC3.2	0.060	0.127	0.522	0.880	1.020
S3	0.140	0.330	0.484	0.640	0.860

The regional vulnerability factor, VR, considers the specific technical, structural and constructive quality of the building at regional level according to the date of construction and the building and seismic design codes in force at that moment. Seven construction periods have been identified (Guardiola-Víllora and Basset-Salom 2015) according to the evolution of the technical standards in Spain.

The first period (prior to 1940) is characterized by pour construction practices and the absence of technical regulations. Furthermore, although since the mid-nineteenth century the first urban police ordinances of Valencia required the signature of a qualified technician for every construction work, it was common practice to find projects without any technical project manager. 72% of the residential buildings of Ground Zero Area belong to this period (33% were built before 1920). All of them have a vertical structural system consisting in load-bearing unreinforced masonry walls without any orthogonal bracing, designed exclusively to resist gravitational loads.

After the Spanish Civil War, the constructive systems and the quality of the materials improved. In the second period, 1941-1962, to which belong about 15% of the residential buildings of Ground Zero Area, the first antecedent of the Spanish technical regulations: “Regulation on restrictions of iron for buildings” (Reglamento sobre las rectricciones del hierro en la edificación 1941) guided the design of the RC framed structures, the prevailing structural typology in Valencia.

The beginning of the third period, 1963-1968, is defined by the publication of the standard MV 101 (1962) "Actions on Buildings”, being compulsory, for the first time, to consider the seismic actions in towns with a Modified Mercalli Intensity (MMI)≥ VII (not applicable in Valencia with MMI=V). It is worth noting the improvement in the quality of materials and design of reinforced concrete structures in this period, favoured by the repeal of the above mentioned “Regulation on restrictions of iron for buildings”. From 1963 on, all the residential building structural typologies in Ground Zero Area (13%) correspond to RC framed structures, RC1 or RC3.2.

During the fourth period, 1969-1974, the seismic requirements were regulated by the first Spanish seismic code, PGS-1 (1968). This document included very basic requirements in terms of static calculation, establishing the facultative application of the seismic actions in Valencia (zone classified as low seismicity) but without any design recommendations.

The fifth period, 1975-1996, is defined by the Seismic Code PDS-1 (1974), which addressed more systematically the structural analysis considering seismic actions. However, with no essential changes in the hazard map with respect to the previous code, including the seismic actions in Valencia (zone of low seismicity) continued to be not mandatory. It is worth nothing that in 1977 the old MV standards were transformed into the new Basic Construction Standards (NBE), a mandatory code leading to a higher control and to an improvement of the quality of the constructive process.

The sixth period (1997-2004) started in 1997, considering the two-year transition to the new Spanish Code for Seismic Design of Buildings, NCSE-94 (1994). This document entailed a significant qualitative improvement, establishing not only new calculation parameters but also design and constructive prescriptions. The application was mandatory for normal importance buildings in areas where the basic seismic ground acceleration (a_b) was equal or bigger than 0.06g which implied the obligation to calculate the structures considering seismic actions and to comply with all the code requirements in Valencia ($a_b = 0.06g$).

After 2004, the enforcement of the Spanish Code for Seismic Design of Buildings NCSE-02 (2002), mandatory for the city of Valencia, improved the seismic detailing requirements to achieve better ductile behaviour. Only 1.7% of the residential buildings in Ground Zero Area belong to this period.

Table 2 shows the regional vulnerability factors for the building typologies in Ground Zero Area. These modifiers have been defined taking into account the aforementioned periods, the similarities in the materials quality, construction process and structural characteristics of the buildings in this area with the buildings in other districts in Valencia (Guardiola-Víllora and Basset-Salom 2015) or in Barcelona (Lantada 2007; Lantada et al. 2010) as well as from the studies of the performance of masonry and RC buildings damaged during Lorca May 11th 2011 earthquake (Feriche et al. 2012; Basset-Salom and Guardiola-Víllora 2014; Martinez-Cuevas and Gaspar-Escribano 2016).

Table 2 Regional Vulnerability factors, VR, for the building typologies in Ground Zero Area

PERIOD	Seismic code level	TYPOLOGY			
		M3.1	M3.3	S3	RC1-RC3.2
<1940	No code	0.120	0.234		
1941-1962	No code	0.100	0.171	0.171	0.228
1963-1968	No code				0.228
1969-1974	Low code				0.100
1975-1996	Low code				0.100
1997-2004	Medium code				0.080
> 2004	High code				00

To take into account the specific characteristics of each building, and its location within the block, the behaviour modifiers, Vm, increase or decrease the Vulnerability Index V_I*, when contributing negatively or positively, respectively, to their seismic performance. These factors are related to the building itself (plan and elevation configuration, state of preservation, type and quality of materials, number of storeys, geometric and stiffness irregularities, etc.) and to the aggregate building position and elevation with respect to the adjacent buildings. Their calibration and quantification have been adjusted by different authors (Milutinovic and Trendafiloski 2003; Giovinazzi and Lagomarsino 2004; Giovinazzi 2005; Lantada 2007; Lantada et al. 2010; Feriche et al. 2012; Martinez-Cuevas et al. 2017), based on the seismic response and the level of damage of both masonry and RC residential buildings in recent earthquakes.

The applicability of these modifiers depends on the level of detailed information available for the building stock. In the case of Ground Zero Area, this information has been retrieved from several sources such as the cadastral database, the Municipal Historical Archive of Valencia, the preliminary documents of the PEC, PhD Thesis

(Pastor Vila 2012, Herrero García 2016), and from a comprehensive field survey of the whole area carried out by the authors. All the data have been implemented in a database, linked to the corresponding gvSIG (gvSIG association 2009) mapping tool. The behaviour modifiers adopted for Ground Zero Area are summarized in table 3.

Table 3: Behaviour modifiers, Vm, for the building typologies in Ground Zero Area

Vulnerability factors	BEHAVIOUR MODIFIERS Vm	
	M 3.1 - M 3.3	RC1 - RC3.2 - S3
Number of storeys	1-2 storeys: -0.02 (≤ 1940) -0.04 (> 1940) 3-5 storeys: +0.02 (≤ 1940) 0 (> 1940)	1-3 storeys: -0.04 4-7 storeys: 0 ≥ 8 storeys: +0.08
Façade Length (L>15m)	((0.04*façade length)/15)-0.04	Not applicable
Horizontal irregularity	rc < 0,5: +0,04 0,5 ≤ rc ≤ 0,7: +0,02	
Vertical irregularity	δ ≤ 1: 0 1 <δ ≤3: +0.02 δ> 3: +0.04	
State of preservation	Bad: +0.04 Good: -0.04	
Aggregate building position	Header: +0.06 Corner: +0.04 Middle: -0.04	
Aggregate building elevation (adjacent buildings of different height when Δh≥ 2 storeys)	-0.04 ÷ +0.04	

The building modifiers include the number of storeys, the façade length in the case of masonry buildings (Lantada 2007) when longer than 15 m (10.2% of the masonry building stock), the geometric irregularities both in plan (horizontal irregularity) and elevation (vertical irregularity) and the state of preservation. Other modifiers such as the soft story and short column are not applicable in Ground Zero Area because there are no buildings with these stiffness irregularities. The number of storeys above ground is a factor which penalises or improves the building performance. In the case on the masonry buildings, the date of construction has been taken into account, because of the improvement of the constructive quality of the buildings after 1940. The horizontal irregularity modifier has been defined (Lantada 2007) based on the compactness ratio (rc) which relates the area of the building and the area of the circle with the same perimeter. The modifier considering the irregularity in elevation takes into account the possibility of having floors in a building with different built areas. It is calculated from the coefficient δ which represents the difference between the number of floors in the analysed building and the number of floors of an equivalent regular building with the same volume and plan area (Lantada 2007). The state of preservation has been proven to be a determinant factor in lowering vulnerability of structures in historic city centres and in improving their seismic performance, especially in the case of unreinforced masonry buildings (Basset-Salom and Guardiola-Víllora 2013).

The location modifiers account for the relative position of the building with respect to the rest of the buildings in the same block, as well as for the difference in height with its adjacent buildings when greater than, or equal to, two storeys. The aggregate building position is a relevant factor, being the corner and header buildings the most vulnerable (Milutinovich and Trendafiloski 2003). Buildings located in the middle of the block but adjacent to a long-term empty plot have been considered as corner or header buildings. When adjacent buildings have different heights, damage produced by earthquake is bigger due to pounding. Values assigned to the aggregate building elevation modifier range from -0.04 to +0.04 (Lantada et al. 2010).

The map representing the seismic vulnerability index of each building in Ground Zero Area is shown in Figure 9, including the percentages as well as the number of buildings in total and for each structural typology. Plots in grey (not evaluated) are either empty or correspond to ruins or non-residential buildings.

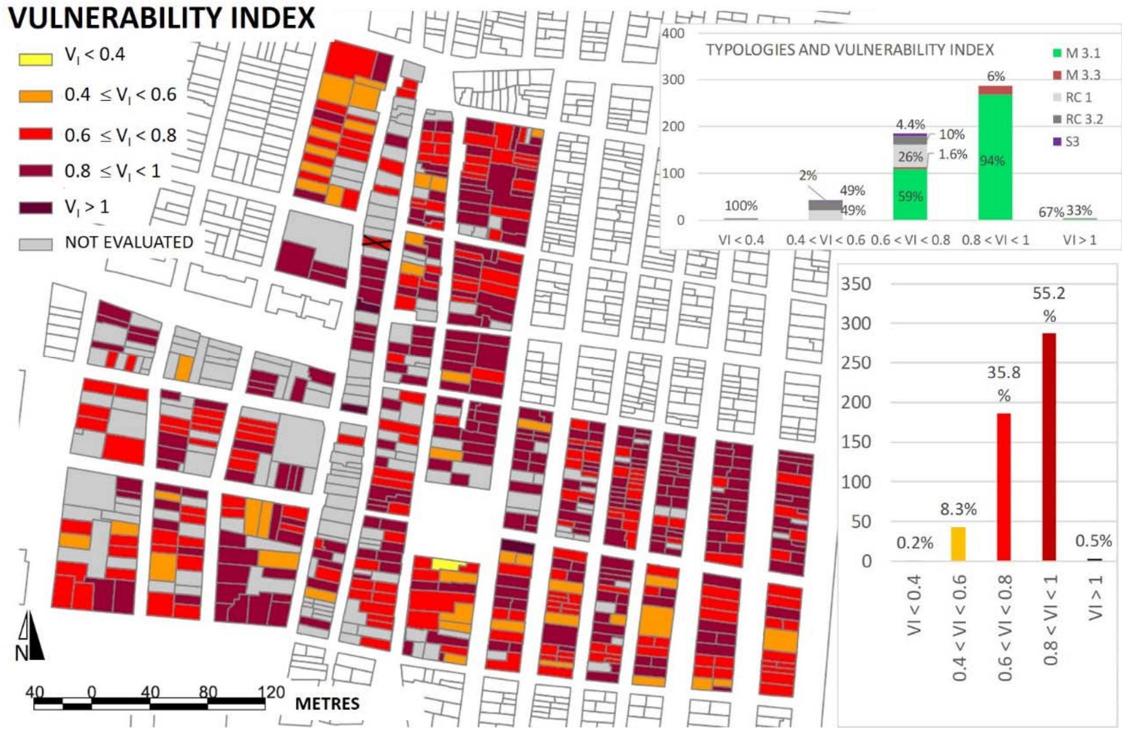

Figure 9. Map of Vulnerability Indices of residential buildings in Ground Zero Area. Percentage and number of residential buildings in total and for each structural typology

This vulnerability index distribution in Ground Zero Area shows the low seismic quality of the buildings. Most of them (55.2%) have a final vulnerability index (sum of the representative value and all the modifiers) bigger than 0.8, being 35.8% within the interval [$0.60 < V_I \leq 0.82$]. The vulnerability indices of masonry buildings (M3.1, M3.3) range from 0.7 to 1.02, for reinforced concrete buildings (RC1 and RC3.2) from 0.5 to 0.77 and for steel buildings (S3) from 0.57 to 0.71, being the most vulnerable buildings those located at the headers of the block or adjacent to empty plots, as expected. Figure 10 shows some of the buildings with the highest vulnerability indices.

According to the vulnerability index and the vulnerability membership functions (Milutinovic and Trendafiloski 2003), all the residential buildings have been classified into one of the six vulnerability classes (Grünthal 1998): A (highest vulnerability) to F (lowest vulnerability), which describe the ability to withstand seismic loads. The map of the vulnerability classes is represented in Figure 11, including the percentages and the number of buildings in total and for each structural typology and building tenure.

A significant part of the residential building stock belongs to class B (52%), with a high percentage of buildings of class A (33%). All the masonry buildings (M 3.1 and M 3.3) belong to these two classes. The percentage of buildings corresponding to classes C and D (RC 1, RC 3.2 and S3) is 13.7% and 1.3% respectively.

Figure 10. Buildings in Ground Zero Area with the highest vulnerability indices (credit: the authors)

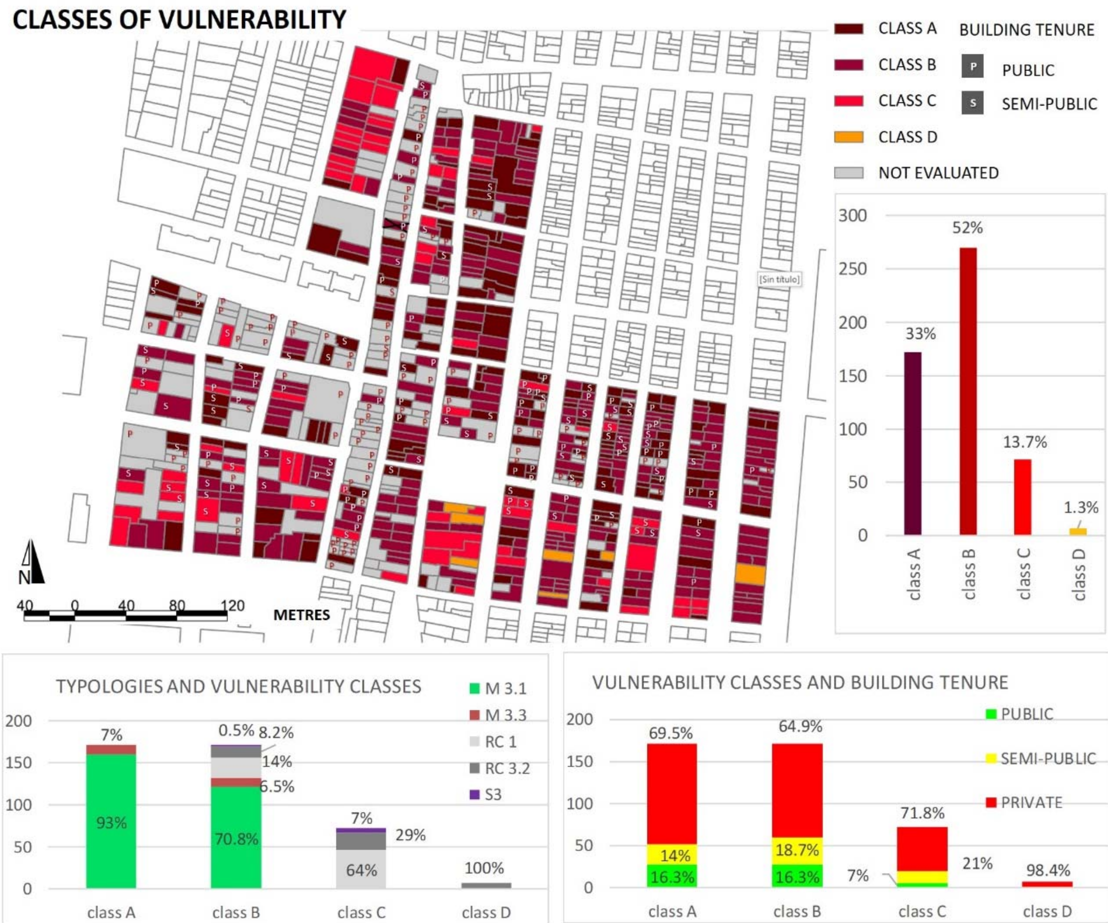

Figure 11. Map of Vulnerability classes according to EMS-98 in Ground Zero Area. Percentage and number of residential buildings in total and for each structural typology and building tenure

It is worth noting that 16.3% of the buildings of class A are publicly owned (28 out of 171: 26 M3.1 and 2 M3.3), and 14% are semi publicly owned (23 M3.1 and 1 M 3.3). With regards to class B, 10.3% have a public tenure (28 out of 271: 20 M3.1, 1 M3.3, 4 RC1, 2 RC3.2 and 1 S3) and 11.8% a semi-public one (23 M 3.1, 6 RC1, and 3 RC 32). In summary, 112 buildings of class A or B are totally or partially owned by the city council or a public corporation. These buildings were expropriated and abandoned by the previous city government team, being today in a lousy state. In fact, most of the not-evaluated buildings (ruins or empty plots) are publicly owned. The positive side is that it will be easier to undertake appropriate measures to reduce the vulnerability of the buildings under these circumstances, when included in the planned interventions, provide that there is a real will of the authorities to do so.

Seismic Hazard Scenarios

Deterministic and probabilistic Seismic hazard scenarios, evaluated in terms of macroseismic intensity, have been considered for the damage assessment of Ground Zero Area.

To establish the value of the intensity in the deterministic scenario, the records of the largest historical earthquakes near the city of Valencia have been taken into account (Giner, Molina, and Jauregui 2003; Silva et al. 2019). Three earthquakes are worth mentioning: Tabernes de la Valldigna in 1396 (55.9 km from Valencia), Estubeny in 1748 (63.4 km from Valencia) and Carlet in 1872 (33.8 km from Valencia). The strongest closest event that has ever affected the site is Carlet Earthquake with an EMS-98 intensity of VII. The information provided by the regional maps of expected seismic intensity has been crucial to define the probabilistic earthquake scenarios (URSUA 2010). The effects of the geotechnical zonation in the region have also be considered. The map for a return period of 500 years including soil effects is shown in Figure 12.

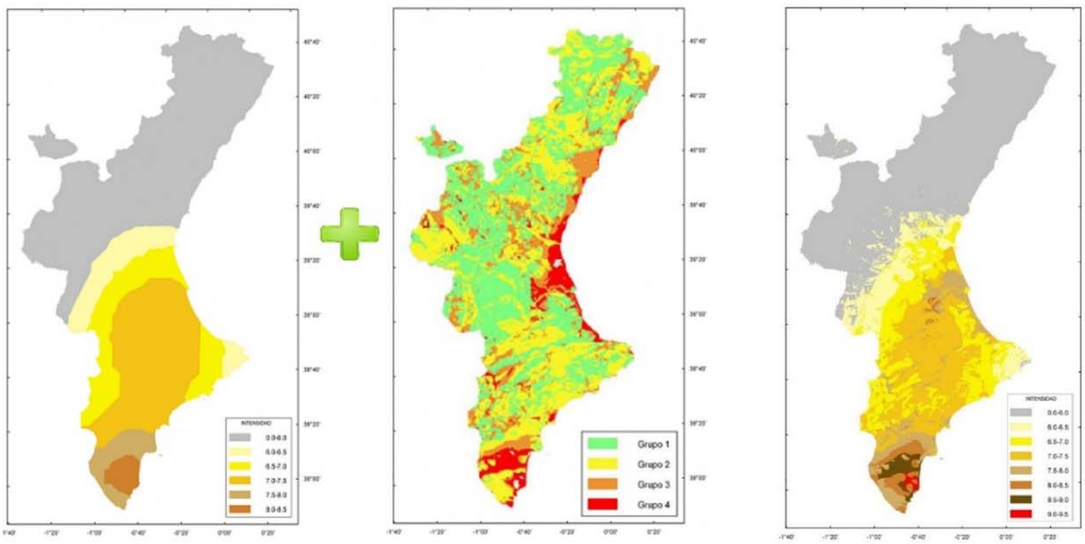

Figure 12. Valencian Community a) Map of expected seismic intensity for a return period of 500 years. b) Soil groups classification c) Map of expected seismic intensity including soil effects (Source: URSUA, 2010)

According to the map, the intensity ranges from VI to VII-VIII (in half-degree intervals). Besides, the basic acceleration (a_b) assigned to Valencia in the Spanish Seismic Code NCSE-02 (2002) is 0.04g which corresponds to a macroseismic intensity of VI (NCSE-94 1994) and the Valencian Community Plan of Seismic Risk (DOGV

2011) establishes an intensity 7.5 (VII-VIII) for the entire municipality. Therefore, three scenarios have been considered for Ground Zero Area: a deterministic scenario with intensity VII and two probabilistic scenarios, with intensities VI and VII-VIII (minimum and maximum respectively).

Seismic Damage scenarios

The likely seismic damage of each building is characterized by the mean damage grade μ_D, defined by a semi-empirical vulnerability function (Milutinovic and Trendafiloski 2003; Giovinazzi 2005) expressed by the following analytical equation:

$$\mu_D = 2{,}5 \cdot \left[1 + \tanh\left(\frac{I + 6{,}25 \cdot V_I - 13{,}1}{2.3}\right)\right] \quad (2)$$

where V_I is the vulnerability index and I is the macroseismic intensity according to the European Macro-seismic Scale EMS-98 (Grünthal 1998).

The distribution of the damage probability is defined by using the continuous beta probability density function (eq 3) which is equivalent to the binomial function adjusting the parameters t and r (Giovinazzi 2005).

Beta function: $$p_\beta(x) = \frac{\Gamma(t)}{\Gamma(r)\,\Gamma(t-r)} \frac{(x-a)^{r-1}\,(b-x)^{t-r-1}}{(b-a)^{t-1}} \quad a \le x \le b \quad a = 0 \quad b = 6 \quad (3)$$

where $t = 8$ $\quad r = t\,(0.007\,\mu_D^3 - 0.0525\,\mu_D^2 + 0.2875\,\mu_D)$

The probability (eq 4) associated to each damage grade k (ranging from 0 to 5) is then calculated, with a beta cumulative density function (eq 5), obtaining the damage probability matrices (DPM) for each seismic intensity in Ground Zero Area (table 4).

$$p(k) = \int_k^{k+1} p_\beta\,(y)dy = P_\beta(k+1) - P_\beta(k) \quad (4)$$

$$P_\beta(k) = \int_0^x p_\beta\,(y)dy \quad (5)$$

The distributions of damage grades (D0: No damage, D1: Slight, D2: Moderate D3: Substantial to Heavy, D4: Very Heavy, and D5: Destruction) considering all the residential buildings and separately for masonry and concrete typologies (M3.1/M3.3 and RC1 / RC 3.2) are illustrated in Figure 13. Despite being Valencia an area of low to moderate seismicity, moderate (D2), substantial to heavy (D3) and very heavy (D4) damage are expected, since most of the residential buildings in Ground Zero Area belong to classes A and B.

Even though the probability exists for some buildings to remain undamaged (56.6%, 25.2% and 14% for intensities VI, VII and VII-VIII) or to undergo slight damage (29.3%, 34% and 28% for intensities VI, VII and VII-VIII), a relevant number of residential buildings are expected to exhibit moderate damage (11%, 25.6% and 30% for intensities VI, VII and VII-VIII), substantial to heavy damage (2.7%, 12% and 19.8% for intensities VI, VII and VII-VIII) and even heavy damage (0.3%, 2.96% and 7.1% for intensities VI, VII and VII-VIII). The most significant damages are related with the most vulnerable typologies, M 3.1 and M 3.3, in which heavy damage may occur, while RC and Steel buildings will suffer mostly slight damage.

Finally, to facilitate mapping and, subsequently, damage distribution analysis, a weighted mean damage index, DSm, is calculated from the probability of occurrence of each damage grade, P [DS_k], with the following expression:

$$DS_m = \sum_{k=0}^{5} k \cdot P[DS_k] \quad (7)$$

Table 4 Damage Probability Matrices (DPM) for the maximum and minimum values of the Vulnerability Index for each structural typology and scenario.

GROUND ZERO				μd	Probability of each damage grade						DSm
	Typology	V_I			D0	D1	D2	D3	D4	D5	
Intensity VI	M 3.1	min	0.7000	0.4276	0.7556	0.1962	0.0421	0.0058	0.0003	0.0000	0.2990
	27.4%	max	1.0227	1.7540	0.0897	0.3261	0.3473	0.1883	0.0463	0.0022	1.7820
	M 3.3	min	0.7240	0.4815	0.7145	0.2250	0.0524	0.0077	0.0005	0.0000	0.3547
	10.6%	max	1.0175	1.7214	0.0957	0.3335	0.3441	0.1813	0.0433	0.0020	1.7489
	RC1	min	0.5020	0.1545	0.9373	0.0545	0.0075	0.0007	0.0000	0.0000	0.0717
	15%	max	0.7700	0.6017	0.6218	0.2847	0.0791	0.0134	0.0010	0.0000	0.4872
	RC3.2	min	0.3820	0.0817	0.9715	0.0252	0.0030	0.0003	0.0000	0.0000	0.0320
	15%	max	0.7620	0.5791	0.6391	0.2741	0.0737	0.0122	0.0009	0.0000	0.4616
	S 3	min	0.5750	0.2263	0.8963	0.0885	0.0137	0.0014	0.0001	0.0000	0.1205
	12.4%	max	0.7150	0.4606	0.7305	0.2139	0.0483	0.0069	0.0004	0.0000	0.3328
Intensity VII	M 3.1	min	0.7000	0.9121	0.4039	0.3883	0.1640	0.0397	0.0042	0.0001	0.8522
	27.4%	max	1.0227	2.8159	0.0079	0.0998	0.2760	0.3558	0.2241	0.0365	2.7978
	M 3.3	min	0.7240	1.0135	0.3444	0.4038	0.1934	0.0521	0.0061	0.0001	0.9720
	10.6%	max	1.0175	2.7804	0.0087	0.1053	0.2825	0.3539	0.2159	0.0337	2.7641
	RC1	min	0.5020	0.3535	0.8107	0.1557	0.0297	0.0037	0.0002	0.0000	0.2271
	15%	max	0.7700	1.2305	0.2393	0.4098	0.2530	0.0850	0.0126	0.0003	1.2227
	RC3.2	min	0.3820	0.1906	0.9175	0.0711	0.0104	0.0010	0.0000	0.0000	0.0951
	15%	max	0.7620	1.1906	0.2564	0.4112	0.2427	0.0783	0.0111	0.0003	1.1773
	S 3	min	0.5750	0.5081	0.6939	0.2388	0.0579	0.0088	0.0006	0.0000	0.3832
	12.4%	max	0.7150	0.9745	0.3665	0.3989	0.1821	0.0471	0.0053	0.0001	0.9261
Intensity VII-VIII	M 3.1	min	0.7000	1.2816	0.2187	0.4066	0.2658	0.0938	0.0146	0.0004	1.2801
	27.4%	max	1.0227	3.3285	0.0017	0.0389	0.1708	0.3385	0.3445	0.1056	3.3021
	M 3.3	min	0.7240	1.4098	0.1735	0.3925	0.2949	0.1175	0.0208	0.0007	1.4215
	10.6%	max	1.0175	3.2964	0.0019	0.0417	0.1776	0.3422	0.3375	0.0992	3.2692
	RC1	min	0.5020	0.5257	0.6803	0.2478	0.0617	0.0096	0.0006	0.0000	0.4024
	15%	max	0.7700	1.6760	0.1047	0.3436	0.3390	0.1717	0.0393	0.0017	1.7025
	RC3.2	min	0.3820	0.2884	0.8563	0.1206	0.0207	0.0024	0.0001	0.0000	0.1695
	15%	max	0.7620	1.6279	0.1150	0.3538	0.3328	0.1616	0.0354	0.0015	1.6530
	S 3	min	0.5750	0.7437	0.5164	0.3423	0.1159	0.0233	0.0020	0.0000	0.6522
	12.4%	max	0.7150	1.3608	0.1898	0.3989	0.2844	0.1082	0.0183	0.0005	1.3680

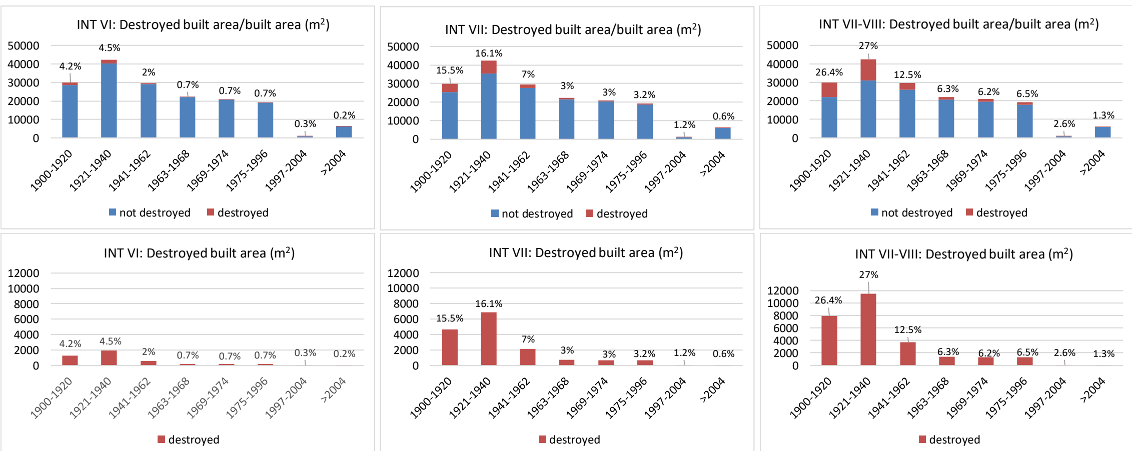

Figure 13 Probable Distribution of damage grades in all the structural typologies, the masonry (M3.1, M3.3) and the RC (RC1, RC 3.2) typologies

Figure 14 displays, the distribution of the estimated mean damage index in Ground Zero Area building stock for each seismic scenario to identify the more vulnerable buildings. The values of DSm (see table 4) range from 0.032 to 1.78 (intensity VI), 0.09 to 2.8 (intensity VII) and 0.17 to 3.3 (intensity VII-VIII); the minimum value corresponding to RC3.2 and the maximum to M 3.1.

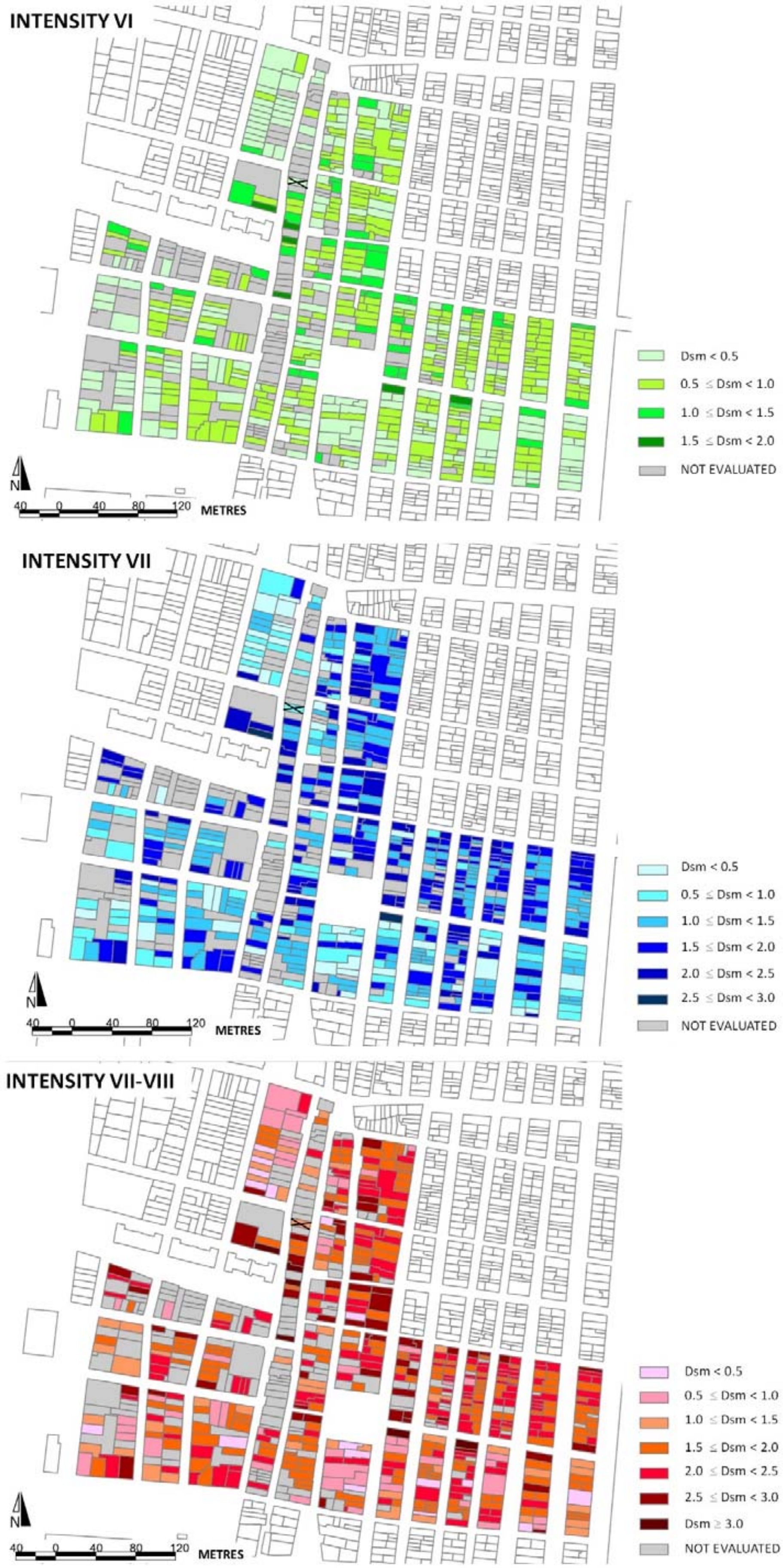

Figure 14 Mean damage index distribution (Dsm) for intensity VI, VII and VII-VIII

Economic loss estimation

After assessing the physical damage, the economic losses have been estimated. These losses are expressed in terms of the equivalent built area which is expected to be destroyed by the earthquake in each seismic scenario and which, consequently, will need to be replaced or repaired.

This area has been calculated (FEMA-NIBS 2003), by multiplying the floor area of each building (building area in m^2) and the probability of the building being in each given damage state (obtained from the corresponding Damage Probability Matrix). For damage states D4 and D5 a loss ratio of 100% of the building replacement cost is assumed decreasing to 50%, 10% and 2% for D3, D2 and D1, respectively.

The equivalent built area expected to be destroyed for each seismic scenario is represented in the bar diagrams in Figure 15, distributed by built periods and building typologies, respectively (percentages correspond to each category). It is worth noting that, according to these results, in the event of an earthquake of intensity VI, VII, or VII-VIII, about 4259 m^2, 15620 m^2 and 27156 m^2 respectively (2.4%; 9.1% and 15.8% of the residential building stock of Ground Zero Area) will be destroyed, of which about 74% of the destroyed built area corresponds to the first constructive period (1900-1940). It should be highlighted that all the buildings in this period are M 3.1 or M 3.3. As expected, RC and steel buildings will be less affected.

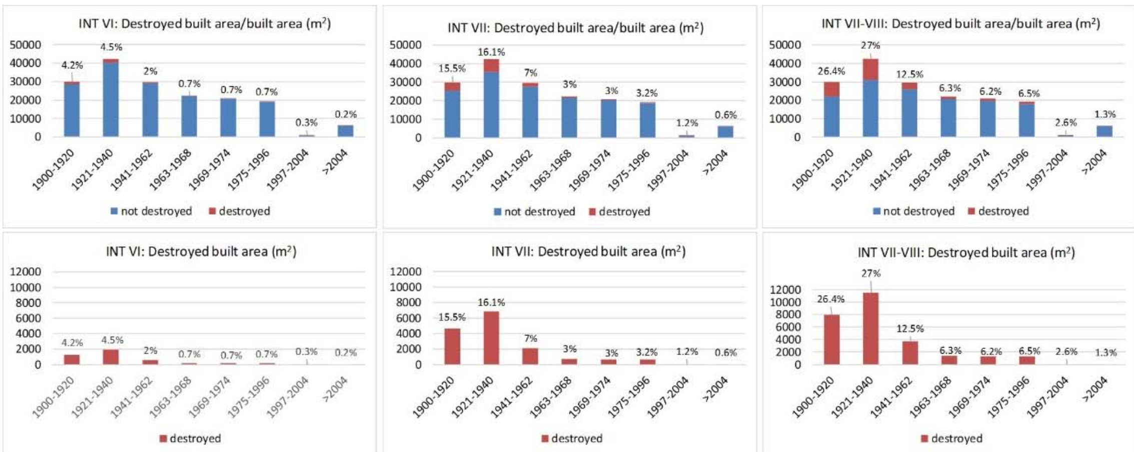

Figure 15 Destroyed built area (in m^2) distributed by built periods and building typologies.

This destroyed equivalent area should not be neglected, especially in the case of typologies M 3.1 and M 3.3, because a significant part corresponds to residential buildings listed with a protection grade 2 or 3 in the Catalogue of listed buildings of the PGOU88 (see Figure 2a), currently in force. According to the diagrams in Figure 16 a, the expected destroyed built area corresponding to residential buildings with a protection grade 2 or 3 has been estimated as 2444 m^2, 8606 m^2 and 14423 m^2 respectively for intensities VI, VII and VII-VIII (8.6%, 30.3% and 50.9% of the destroyed). It is important to stress that about 68% of the destroyed built area of typology M 3.1, corresponds to residential buildings with a protection grade (2 or 3). Similar numbers (Figure 16 b) are obtained if we consider the equivalent destroyed area included in the protected zones BIC (Assets of cultural interest) or BRL (assets of local relevance), defined in the preliminary documents of the PEC to be approved. These figures give an idea of the scope and irreparable loss involved.

Figure 16 Destroyed built area (in m^2) corresponding to protected buildings according to a) PGOU88 and b) PEC 2019 (percentages correspond to each category)

Discussion and conclusions

Even though Ground Zero Area (El Cabanyal) is located in a low-to-moderate seismic zone (as all the neighbourhoods in Valencia), the research carried out shows the high vulnerability of its building stock (mainly unreinforced masonry typologies built before 1940) and consequently foresees a significant number of residential listed buildings to be damaged in the occurrence of a seismic event.

After developing a database including the parameters influencing the seismic response, the vulnerability of each building has been assessed with the Vulnerability Index Method. Results have been mapped with a Geographic Information System, showing the distribution of the vulnerability indices and the expected damage for the considered seismic hazard scenarios. The highest vulnerability indices of the residential buildings correspond to masonry typologies (with 55.2% bigger than 0.8) belonging to classes A and B, while indices in reinforce concrete and steel structures are smaller than 0.77, belonging to classes B, C and, less frequently, to class D.

The high vulnerability is due not only to the fact that they were not designed to withstand horizontal loads and have not been retrofitted to meet current design codes but also because of the poor urban planning, which led to lack of maintenance, progressive decay and subsequent abandonment. Consequently, significant damage can be anticipated, especially for masonry buildings (M3.1 and M3.3). Although for an earthquake of intensity VI most of them will remain undamaged or slightly damaged (about 45% and 34%), 15% will experience moderate damage and 4% substantial to heavy damage. For intensity VII-VIII, the foreseeable seismic damage is predominantly moderate (33%), however, a non-negligible number of residential buildings will suffer substantial to heavy (25%) or heavy damage (10%).

The expected economic losses have been estimated as equivalent destroyed built area. For a seismic scenario of intensity VII-VIII, 15.8% of the total built residential area of Ground Zero will be destroyed, from which 50.9% corresponds to residential buildings with a structural or environmental protection status (grade 2 or 3) according to the Catalogue of Listed buildings of the PGOU88, in force at the moment of writing this paper. Obviously for the seismic scenarios of intensities VI and VII the destroyed equivalent area is smaller but also significant (8.6% and 30.3%, respectively). Despite the economic impact, it should be emphasised that, having the listed buildings an historical, cultural and heritage value, their loss is invaluable and irreplaceable.

In view of these results it can incontestably be concluded that residential buildings in El Cabanyal's Ground Zero Area need an improvement of their seismic response to minimise losses in case of an earthquake and to safeguard the value of the historical heritage.

After years of abandonment, a new period of interventions is starting in the neighbourhood, with the allocation of funds coming for the EU among others, intended to renovate, rehabilitate and retrofit El Cabanyal. There is a significant room to strengthen and enhance their resilience to earthquakes, starting by reducing their seismic vulnerability. A more detailed analysis especially, but not exclusively of protected buildings is advisable in order to define appropriate retrofitting criteria

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FIGURE CAPTIONS

Figure 1. Residential buildings in El Cabanyal (credit: the authors)

Figure 2. Map of the city of Valencia in 1899, by José Manuel Cortina Pérez with the proposal of Casimiro Meseguer (Llopis, Perdigón, and Taberner 2004)

Figure 3. a) PGOU88. Catalogue of listed buildings. b) PEPRI 2001-Proposal, c) PEPRI 2001: buildings to be demolished. d) PEPRI 2001: listed buildings (Source a, d: Valencia City Council, b, c: Herrero García 2016)

Figure 4. PEC, 2019. Information Plan: tenure status (Source: Valencia City Council)

Figure 5. Example of residential buildings in Ground Zero Area with a bad state of maintenance, ruined buildings and empty plots (credit: the authors)

Figure 6. Residential buildings: a) Age b) Number of storeys (Source: Cadastral database)

Figure 7. Structural typologies: a) URM timber floors, b) URM steel floors, c) RC framed structure (credit: the authors). Original plans of structural typologies d) URM timber floors, e) URM steel floors; f) RC framed structure (Source: Municipal Historical Archive of Valencia)

Figure 8. Distribution of the structural typologies in Ground Zero Area: in total, by age (built period) and number of storeys.

Figure 9. Map of Vulnerability Indices of residential buildings in Ground Zero Area. Percentage and number of residential buildings in total and for each structural typology

Figure 10. Buildings in Ground Zero Area with the highest vulnerability indices (credit: the authors)

Figure 11. Map of Vulnerability classes according to EMS-98 in Ground Zero Area. Percentage and number of residential buildings in total and for each structural typology and building tenure

Figure 12. Valencian Community a) Map of expected seismic intensity for a return period of 500 years. b) Soil groups classification c) Map of expected seismic intensity including soil effects (Source: URSUA, 2010)

Figure 13 Probable Distribution of damage grades in all the structural typologies, the masonry (M3.1, M3.3) and the RC (RC1, RC 3.2) typologies

Figure 14. Mean damage index distribution (Dsm) for intensity VI, VII and VII-VIII

Figure 15. Destroyed built area (in m^2) distributed by built periods and building typologies.

Figure 16. Destroyed built area (in m^2) corresponding to protected buildings according to a) PGOU88 and b) PEC 2019 (percentages correspond to each category)