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COMPARING A SIMULATED LOSS SCENARIO WITH THE OBSERVED EARTHQUAKE DAMAGE: THE LORCA 2011 CASE STUDY

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ABSTRACT

A loss assessment was performed for the buildings of Lorca, Spain, considering an earthquake hazard scenario with similar characteristics to those of a real event which occurred on May 11th 2011, in terms of epicentre, depth and magnitude. This low-to moderate earthquake caused severe damage and disruption in the region and especially on the city. A building by building resolution database was developed and used for damage and loss assessment. The portfolio of buildings was characterized by means of relevant indexes capturing information from a structural point of view such as age, main construction materials, number of stories, and building class. A replacement cost approach was selected for the analysis in order to calculate the direct losses incurred by the event. Hazard and vulnerability were modeled in a probabilistic way, considering their inherent uncertainties which were also taken into account in the damage and loss calculation process. Losses have been expressed in terms of the mean damage ratio of each dwelling and since the analysis has been performed on a geographical information system platform, the distribution of the damage and its categories was mapped for the entire urban centre. The simulated damage was compared with the observed damage reported by the local authorities that inspected the city after the event.

INTRODUCTION

On May 11th 2011 a 5.1 (M_W) earthquake stroke the Murcia region in south-eastern Spain, where the city of Lorca, with almost 60,000 inhabitants, was the most affected and damaged place. The epicentre was located 5 km north of Lorca and the depth of the event was estimated at 5 km. The event was associated to the Alhama de Murcia local fault which extends over more than 100 km with a strike-slip-reverse mechanism. In spite of the moderate magnitude of the event, 9 casualties occurred, more than 300 people were injured and around 10,000 people could not return to their houses after the event due the damage to their homes. Two health centres suffered severe structural damage that endangered the security of the patients and medical staff, and were therefore evacuated. According to the damage surveys, around 80% of the inspected buildings presented some degree of damage, though it was generally classified as slight. The damage generated a chaotic situation in the post-disaster phase since there was no prior experience in implementing an emergency plan, and many of the response actions took longer than what was expected by the community (Barbat et al., 2011a).

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According to the post-earthquake damage assessment made by the local municipality, 19% of the existing 7,852 buildings were not inspected given that they suffered only very slight damage, 52% of the buildings were inspected and classified as habitable because of the lack of significant damage, 16% had no significant structural damage but limited access because of non-structural damage, 9% had forbidden access because of high structural damage, and for 4% of the buildings a mandatory demolition order was given (Ayuntamiento de Lorca, 2012).

In this paper the damage and corresponding losses occurred during the Lorca 2011 earthquake are quantified using a probabilistic approach, based on advanced and state-of-the-art methodologies. Seismic hazard is represented through the expected earthquake intensities at ground level that include the mean values and their associated variance. A building by building resolution exposure database was defined for the public and private buildings of Lorca, capturing relevant information in terms of structural parameters and building classes. Updated indexes from the latest housing census (INE, 2011) were used to identify and assign the building classes. To quantify the physical vulnerability of buildings, vulnerability functions that take into account the uncertainties related to the accuracy of building data and seismic structural behaviour were used. A unique vulnerability function was assigned to each building class identified in Lorca. The convolution between the hazard and the vulnerability provides the expected losses. Only direct physical losses were accounted for in the analysis by calculating the mean damage ratio (MDR) of each building of the exposure database; second order effects, such as business disruption, damage to cars and other indirect damage and the socio-economic impact, were not included in the estimation. The latter can be included if complementary information is available using approaches like those proposed by Cardona (2001); Carreño (2006); Carreño et al. (2007; 2012); Barbat et al. (2011b). The obtained results have been compared with those observed after the 2011 Lorca earthquake and reported by the local authorities (Ayuntamiento de Lorca, 2012). The outcome of this comparison will allow improving the probabilistic risk assessment methodologies in terms of their relevance and understanding.

Insured losses were quantified in 489 millions of euros where most of the claims were related to households and commercial units (CCS, 2012). This number does not correspond to the total cost of the earthquake's damage in Lorca because not all insurance policies have the same conditions, and the insured limits and deductibles are not included in this amount.

Previous studies to estimate seismic losses in the Murcia region have been performed in the recent past. The first one was conducted before the 2011 earthquake (Benito et al. 2005) where the probability of exceeding certain damage levels was obtained for the Murcia region. The second was performed after the earthquake, using a probabilistic approach to estimate future losses expressed in terms of the loss exceedance curve (Valcárcel et al., 2012).

Several tools are available to perform a seismic risk assessment in probabilistic metrics. CAPRA[5] platform (ERN-AL, 2010; Cardona et al., 2010, 2012; Salgado et al., 2013a; 2013b) which consists of different modules enabling the evaluation of the seismic hazard, earthquake vulnerability and seismic risk was selected for the analysis. The Lorca case constitutes an opportunity and a challenge to understand the strengths and weaknesses of the probabilistic seismic risk evaluation approach, highlighting the improvements required regarding exposure input data as well as for hazard, vulnerability and risk assessment.

PROBABILISTIC SEISMIC HAZARD ASSESSMENT

The probabilistic risk assessment methodology that is applied in this study requires an exhaustive set of stochastic scenarios that characterize, in a comprehensive way, the seismic hazard in Lorca. To represent the seismic hazard in this way, the best approach was to conduct a probabilistic and spectral seismic hazard analysis in the Iberian Peninsula and its neighbouring regions. Accordingly, a seismic hazard assessment is performed considering different seismogenetic sources that were characterized

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[5] Comprehensive Approach to Probabilistic Risk Assessment

by a Gutenberg-Richter (G-R) (1944) model. The employed tectonic zonation corresponds to the one proposed in the framework of the SHARE project (GRCG, 2010) where 51 seismogenetic sources were defined. An additional source was located in northern Africa to account for the seismicity occurring in that area which may affect the Peninsula. Since the occurrence of earthquakes over the time cannot be predicted, and a complete time window is an unknown quantity, a set of 1,991 stochastic events was generated using the CRISIS 2007 software (Ordaz et al., 2007). To characterize the seismicity occurrence process at each source, a Poisson model was selected. Seismic activity is determined based on the magnitude recurrence rates, relating the frequencies with which earthquakes with a given magnitude occur at each seismogenetic source.

Once the set of stochastic scenarios was generated, an event with similar characteristics in terms of location and magnitude was selected to conduct the damage analysis on the buildings of Lorca. Figure 1 shows the shakemap of the selected event which is associated to the *ESAS250* seismogenetic source (GRCG, 2010) which is located beneath the city of Lorca. Intensities are computed at bedrock level and no local site-effects are taken into account in the analysis since no information to generate spectral transfer functions was available for the city.

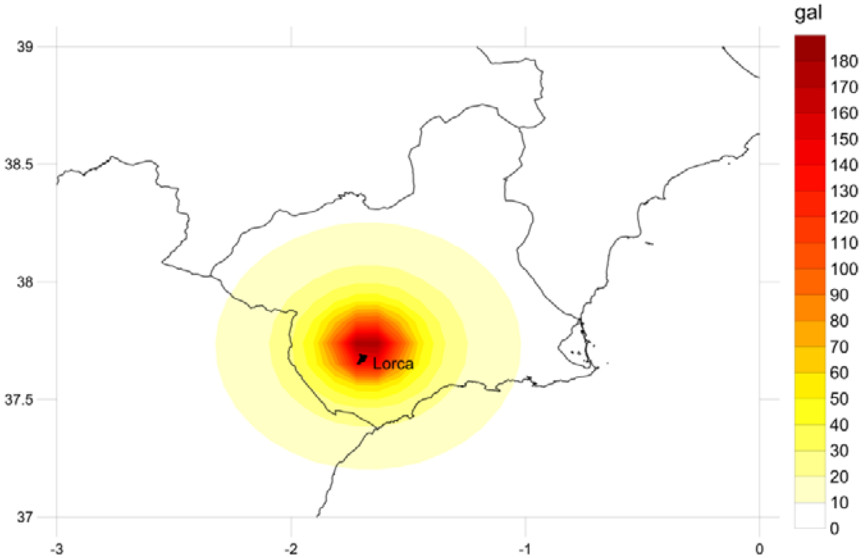

Figure 1. PGA (cm/s^2) for the selected scenario

INVENTORY OF EXPOSED ASSETS

For a probabilistic risk assessment, the required database comprised by the portfolio of the exposed buildings of Lorca, both public and private, has been assembled. Such databases can be constructed using different scales or resolution levels. For this case, a detailed building by building resolution level was chosen since the required information was available. This process has always presented challenges in modelling since usually the required information is not available directly from a unique source and, in many cases it needs to be inferred or generated through indexes obtained from several sources. In this case, information about the geographical location and structural characteristics such as age, material, structural system, number of stories and building class is required for each element. Those parameters were assigned to each of the elements included in the final database using the data and procedure explained in this section.

Updated cadastral information is available for Lorca (MHAP, 2013) with a building by building resolution level. Since the information was generated for cadastral and tax purposes, several properties other than buildings such as terraces, squares and balconies are originally included. Initially, a total of 42,062 elements were included in the database. After a depuration process, intended to include only the buildings, only 17,017 elements remained; in this process, the buildings classified as ruins (before the 2011 earthquake) by the cadastral office were also removed. The cadastral information contains data about the geographical location and number of stories of each building. Building footprints were compared with an aerial image (ESRI, 2010) and 599 additional elements were included in the database for a total of 17,616 buildings. Most of the buildings in Lorca are classified as low-rise from a structural point of view; i.e., buildings of 1 to 3 stories.

From the most recent Spanish population and housing census (INE, 2011), it is possible to define the age distribution of the buildings in Lorca. Using the data of Table 1, this parameter was assigned to the elements on the database.

Table 1. Age distribution for the buildings in Lorca

Age	Distribution
Before 1900	4.4%
1900-1920	2.8%
1921-1940	4.0%
1941-1950	4.8%
1951-1960	11.1%
1961-1970	13.5%
1971-1980	19.4%
1981-1990	13.3%
1991-2001	13.1%
2002-2011	13.6%

Based on previous studies (Benito et al. 2005) and making use of the age distribution, a vulnerability classification based on the EMS-98 scale (Grünthal 1998) using the data of Table 2 was prepared. It can be seen from the table that structures are classified in categories between A and D on this scale.

Table 2. EMS 98 vulnerability class for the buildings in Lorca according to the age

	EMS98 vulnerability class	A	B	C	D
Age	**Before 1900**	80%	20%	-	-
	1900-1920	72%	28%	-	-
	1921-1940	72%	28%	-	-
	1941-1950	69%	28%	3%	-
	1951-1960	46%	49%	5%	-
	1961-1970	18%	38%	44%	-
	1971-1980	5%	40%	55%	-
	1981-1990	-	38%	57%	5%
	1991-2001	-	28%	62%	10%
	2002-2011	-	18%	69%	13%

Based on INE (2011) a base value of 1,247 euros per constructed square meter was established for the city; in addition to this, and in order to take into account the fact that all elements do not have the same price, age was selected as a differentiation parameter. Since repairing stone and brick masonry buildings is more expensive than repairing reinforced concrete buildings due to the necessity of specialized manpower, a factor that increases with the age was defined. By using this approach, the total replacement cost of the buildings in Lorca has been established in 6,658 millions of euros.

A vulnerability class according to the EMS-98 scale has been assigned to each building class. Buildings in Lorca are mostly made of different types of masonry (bricks and stone) for the low-rise structures while for medium- and high-rise buildings reinforced concrete (R/C) waffled slab buildings are mostly used (Vielma et al., 2010; 2009). Steel frames and prefabricated R/C structures are found mostly in the industrial facilities of the city.

By combining the above mentioned two parameters for all the elements, a building class was assigned to each dwelling and a total of 10 building classes were identified for the analysis. Table 3 shows a summary of the exposed assets in terms of building classes, number of elements and replacement values of each of them.

Table 3. Summary of exposed assets statistics

Building class	Number of elements	% of dwellings	Exposed value	% of exposed value
Earthen	1,972	11.19	774.1 €	11.63
Stone masonry	1,777	10.09	620.1 €	9.31
Brick masonry	3,757	21.33	1,347.1 €	20.23
Masonry walls and R/C slabs	3,514	19.95	1,352.1 €	20.31
Stone and brick blocks	1,953	11.09	739.7 €	11.11
Steel buildings	177	1.00	103.0 €	1.55
R/C frames with steel braces	170	0.97	86.9 €	1.30
Pre 1995 R/C frames	2,346	13.32	846.4 €	12.71
Prefabricated R/C structures	703	3.99	255.5 €	3.84
Post 1995 R/C frames	1,247	7.08	533.5 €	8.01
TOTAL	**17,616**	**100**	**6,658.2 €**	**100**

From Table 3 it can be clearly seen that most of the buildings in Lorca are made of masonry, concentrating more than 60% of the total both in number and in exposed value. Moreover, waffle slab buildings constitute the majority of the R/C structures in the city (more than 20% of the buildings in the city).

SEISMIC VULNERABILITY OF THE EXPOSED ASSETS

For this study only the physical vulnerability quantification is of interest from a structural engineering perspective. A vulnerability function approach (Miranda, 1999; Ordaz et al., 1998) was selected for the damage and loss calculation process. Damage is represented through a continuous function that relates hazard intensities which in this case is the spectral acceleration for 5% damping, to the MDR, also considering its variance to account for the uncertainties. The value of the dispersion of the MDR changes along the intensity levels, being equal to zero at the extreme values of the interval and taking its maximum value for the intensity corresponding to a mean damage equal to 50%.

Vulnerability functions are a description of the variation of the first two statistical moments of loss with respect to the hazard intensity. A Beta probability distribution function is assigned and, in this case, the mean value and the standard deviation correspond to the mentioned statistical moments. Once this distribution function is computed, all the parameters required to compute risk in a probabilistic way are available (Ordaz, 2000). This approach is compatible with the probabilistic risk assessment approach selected for the study. Each of the building classes has an associated vulnerability function. The replacement cost of each asset is needed to quantify the expected losses in monetary units since what it is obtained at each intensity level is the ratio of the repair cost relative to the total value of the building.

A total of 22 vulnerability functions were used in the analysis, which have been developed for the Global Risk Model by CIMNE et al. (2013) and included in the Global Assessment Report on Disaster Risk Reduction 2013 (UNISDR, 2013). Figure 2 shows the different vulnerability functions from where it is clear that some building classes, especially those made of unreinforced masonry, are far more vulnerable in seismic terms than others, having for the same intensity level a higher associated MDR. The height of the structures is included in the analysis through three different categories: low-rise (L) for buildings between 1 and 3 stories, medium-rise (M) for those that have 4 to 7 stories and high-rise (H) for 8 and more.

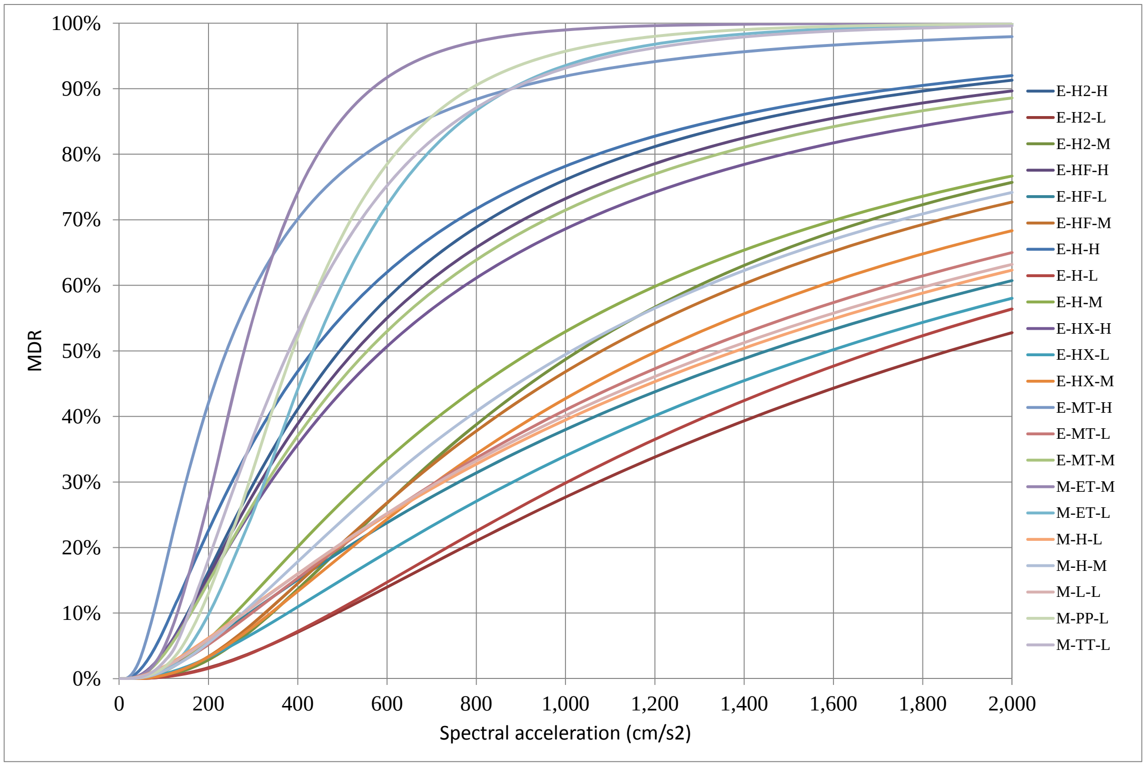

Figure 2. Vulnerability functions used for the buildings in Lorca (L=Low-rise; M=Medium-rise; H=High-rise)

SEISMIC RISK ASSESSMENT

A probabilistic risk analysis is usually conducted for the complete set of stochastic scenarios that are the outcome of a probabilistic seismic hazard assessment. Nevertheless, if it is required, the analysis can be performed for a single scenario. Using the methodology proposed by Ordaz (2000) and used in the CAPRA platform (ERN-AL, 2010), the probability density function is $f(loss_j | Event_i)$ which allows calculating the loss on the j^{th} exposed asset, conditional to the occurrence of the i^{th} scenario. However, it is not possible to calculate this probability distribution directly; therefore, a chaining process between two different conditional probability distributions is required using Eq. 1:

$$f(loss_j \mid Event_i) = \int_0^\infty f(loss_j \mid Sa) \cdot f(Sa \mid Event_i) dSa \qquad (1)$$

where $f(loss_j|Sa)$ has to do with the vulnerability (the expected loss given a hazard intensity) and $f(Sa|Event_i)$ with the hazard (the hazard intensity given the occurrence of the event). Details about the aggregation of the losses can be found in Salgado et al. (2013a) and in Torres et al. (2013).

Seismic risk, when calculated in a probabilistic way, should be expressed in terms of a loss exceedance curve that relates the frequencies with which losses exceeding a certain amount occur. It is usually computed in terms of the annual exceedance rate and calculated by using Eq. 2:

$$\nu(l) = \sum_{i=1}^{N} \Pr(L > l \mid Event_{\mathrm{i}}) \cdot F_A(Event_{\mathrm{i}}) \qquad (2)$$

where $v(l)$ is the rate of exceedance of loss p, N is the total number of hazard scenarios, F_A $(Event_{\,i})$ is the annual frequency of occurrence of the i^{th} hazard event, while $\Pr(L>l|Event_{\,i})$ is the probability of exceeding l, given that the i^{th} event occurred.

When a single scenario approach is selected as in this case, N takes a value equal to 1, while the frequency of occurrence, F_A is set to 1.0. For the selected scenario, the intensities are first calculated for the area under analysis, and then for each asset included in the exposure database the loss and its variance are calculated using the vulnerability functions associated to each element (based on its geographical location and the hazard intensity value at that point). This process is repeated in this case for the 17,616 buildings included in the exposure database. When the risk assessment is performed for a single hazard scenario, a deterministic approach is chosen for the temporal dimension of the hazard while a probabilistic approach still remains for the hazard intensity calculation, vulnerability representation and loss calculation.

In the case of a single scenario approach, the MDR for each building is obtained and aggregated for all the buildings of the city. Results can be disaggregated in terms of building classes to see which classes concentrate higher risk levels.

Table 6 shows the risk results in terms of the aggregated MDR for all the building classes of Lorca considered in this study; from this it is clear that the masonry building classes concentrate the higher physical risk values. Furthermore, it can be seen that the building class with higher MDR corresponds to earthen structures, which have proven to have poor performance under the seismic demand due to the poor construction practices and materials. Masonry structures have the highest MDR values, showing the fact that the stone masonry buildings present the highest risk. R/C slabs also have an important contribution to the modeled losses due to their high seismic vulnerability (Vargas et al., 2013a; 2013b; 2013c; Vielma et al., 2010; 2009).

According to the simulated scenario, a global MDR equal to 8.2% is expected for the buildings of Lorca (see Table 4), which in monetary units and using the replacement cost approach selected for this study corresponds to a total 546.5 million of euros of direct losses.

Table 4. MDR by building class in Lorca

Building class	Damage cost (millions €)	MDR
Earthen	172.8	22.3%
Stone masonry	79.4	12.8%
Brick masonry	75.0	5.6%
Masonry walls and R/C slabs	94.7	7.0%
Toledo masonry	73.8	10.0%
Steel buildings	3.2	3.1%
R/C frames with steel braces	3.2	3.6%
Pre 1995 R/C frames	21.7	2.6%
Prefabricated R/C structures	13.2	5.2%
Post 1995 R/C frames	9.4	1.8%
TOTAL	**546.5**	**8.2%**

Since the risk assessment has been performed on a geo-coded database, the geographical distribution of the damage can also be geo-referenced and risk maps, in terms of the MDR, can be obtained for Lorca (see Figure 3).

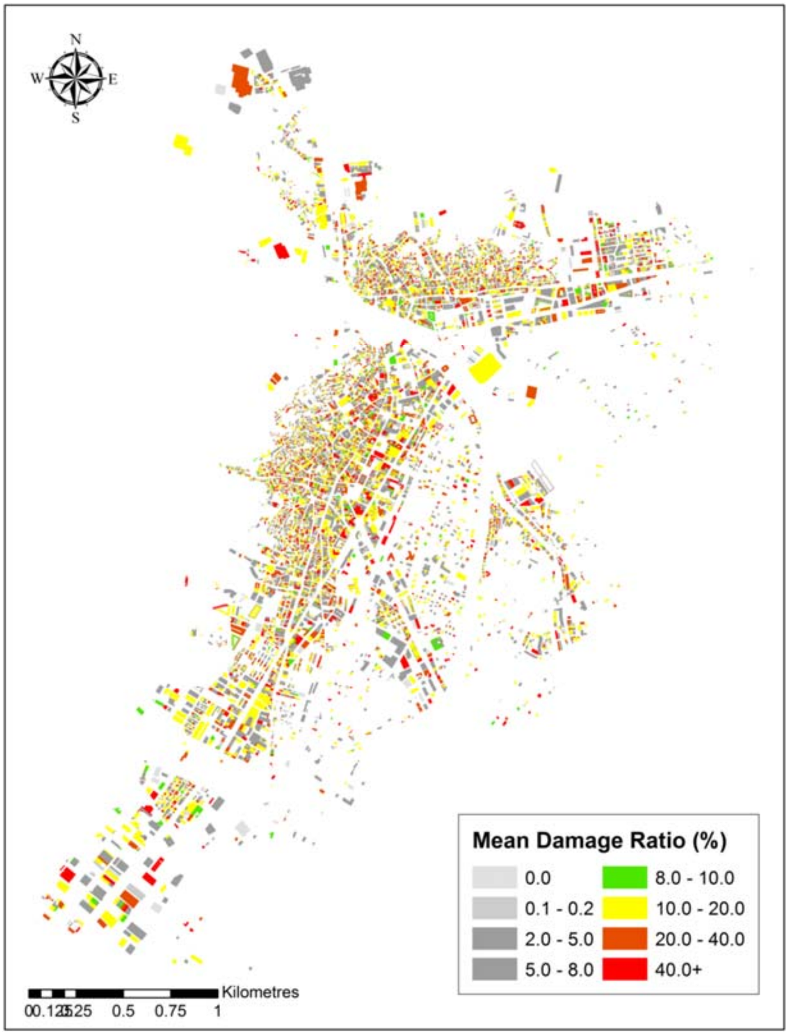

Figure 3. MDR distribution obtained for Lorca

A comparison between the damage observed in Lorca according to the official report of the local authorities (Ayuntamiento de Lorca, 2012) and the scenario simulated in this work was made. According to the inspections, the damaged buildings were classified in four categories: 1) habitable, without significant damage; 2) with restricted access due to non-structural damage endangering the safety of the occupants; 3) with forbidden access because retrofitting actions were required; and 4) buildings with mandatory demolition orders. A total of 7,852 buildings were inspected, accounting for 44.5% of the buildings in Lorca, and it was observed that 19% of those did not suffer any significant damage.

Table 5. Observed damage statistics in Lorca

Damage category	**Number of buildings**	**% of buildings**
No damage	1,492	19.0
Habitable	4,083	52.0
Non-structural damage	1,256	16.0
Structural damage - forbidden access	707	9.0
Demolition order	314	4.0
Total damaged buildings	**6,360**	**81.0**

In order to compare the observed with the simulated damage, MDR levels were set for the different damage categories. It is assumed that buildings need a demolition order if MDR is higher than 40%; have forbidden access if MDR is between 20 and 39.9%; have restricted access if MDR is between 10 and 19.9%; are habitable if MDR is between 6 and 9.9%; and have no damage if MDR is lower than 6%. According to these levels, the statistics for all buildings in Lorca is presented in Table 6.

Table 6. Damage categories statistics from the simulated scenario

Damage category	**MDR (%)**	**Number of buildings**	**% of buildings**
No damage	0.0 - 5.9	3,206	18.2
Habitable	6.0 - 9.9	8,904	50.5
Non-structural damage	10.0 - 19.9	3,606	20.5
Structural damage - forbidden access	20.0 - 39.9	1,897	10.8
Demolition order	>40.0	3	0.0
TOTAL		**17,617**	**100**

The percentage values of the simulated scenario are similar in all damage categories with the exception of the buildings with demolition order. In Lorca many buildings were not demolished because they presented a high level of damage but due to social, institutional and insurance reasons. Figure 4 shows the simulated results grouped in damage categories. Only buildings with restricted access (yellow), forbidden access (red) and demolition orders (purple) have been mapped.

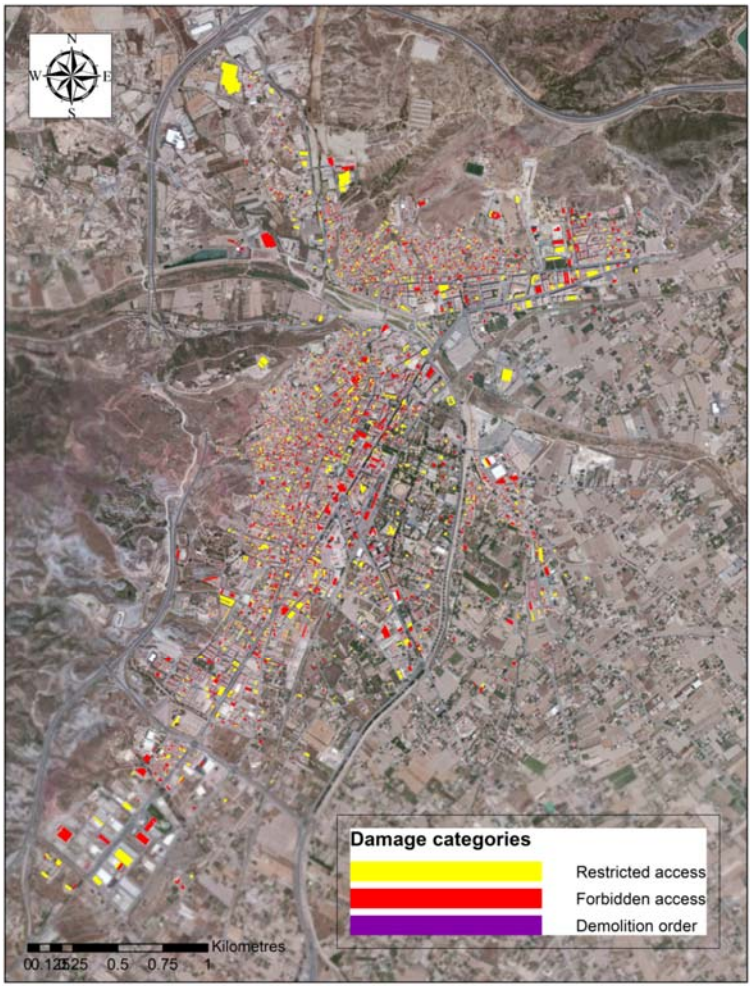

Figure 4. Simulated damage categories for Lorca

As it is well known, physical risk estimations are intended to provide an order of magnitude of the expected losses and their average frequency of occurrence if a loss exceedance curve is computed, and to predict the exact damage and its geographical location in the area under analysis. The objective of this article is to compare the results of observed and simulated damage and loss. A model calibration is not possible from a methodological point of view because it cannot be based on a unique observed damage case. Since catastrophic risk models are mostly intended to work on a global basis, a single event is clearly not statistically significant. Moreover, catastrophic events have low occurrence frequencies and thus there are no sufficient observed damage and loss records available which can be used in a comprehensive calibration process. Obviously, even if a catastrophic risk model is adjusted to match the observed damage for a unique event, this does not guarantee the reliability for a different event at a different location with different characteristics.

CONCLUSIONS

Earthquake risk models at urban level provide overall estimations that can be useful for decision-makers in terms of required resources and expected damage of the portfolio even if the exact location cannot be established. Therefore, if the results are mapped, a building by building resolution level risk assessment can be misleading since the simulated results could be interpreted as an exact prediction for each building, whilst they only represent mean values. Therefore, results in the best case should be grouped by categories, such as building classes, neighborhoods, counties, etc.

This study presents a comparison between the observed and simulated damage in Lorca for an earthquake which characteristics have been defined similar to that occurred on May 2011. Damage levels have the same order of magnitude, showing that probabilistic approaches, such as the selected for this assessment, are useful for the risk quantification process, though they do not match exactly the actual observed values.

From the observed damage point of view, there are several challenges regarding how damage was recorded and classified if a loss evaluation calibration process is performed. Usually qualitative damage scales are used, and therefore, no formal ways to translate those observed damage into loss exist. It is also difficult to capture the damage cost since usually after a large event strikes a city, price increases driven by inflation and scarcity of materials occur and are not easy to be distinguished and included in risk assessment.

Finally it is worth mentioning that after a disaster event there are decisions made not necessarily following technical reasons but economic and urban planning ones. Disaster events may trigger economic boost initiatives, generate new open public space areas and/or stock replacement (even more when resources are available through an insurance consortium). Those actions are not predictable since they depend in each case on the economic circumstances of the event’s occurrence.

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REFERENCES

Ayuntamiento de Lorca (2012) “Visor geográfico seismo de Lorca del 11 de mayo de 2011”, http://www.lorca.es/seismo11demayo/seismo11demayo.asp?id=1540. Accessed on January 03, 2014.

Barbat A, Carreño M, Figueras S, Goula X, Irizarry J, Lantada N, Macau A, Valcárcel J (2011a) El terremoto de Lorca del 11 de mayo de 2011. Institut Geològic de Catalunya-IGC. Barcelona.

Barbat A, Carreño M, Cardona O, Marulanda M (2011b) Evaluación holística del riesgo sísmico en zonas urbanas. *Revista Internacional de Métodos Numéricos para Cálculo y Diseño en Ingeniería*. 27(1):3-27.

Benito B, Carreño E, Jiménez M, Murphy P, Martínez J, Tsige M, Gaspar J, García M, García J, Canora C, Álvarez J, García I (2005) Riesgo Sísmico en la Región de Murcia – RISMUR. Instituto Geográfico Nacional. España.

Cardona O (2001) Estimación holística del riesgo sísmico utilizando sistemas dinámicos complejos. Ph.D. Thesis, Universidad Politécnica de Cataluña. Barcelona, Spain.

Cardona O, Ordaz M, Reinoso E, Yamín L, Barbat A (2012) CAPRA – Comprehensive Approach to Probabilistic Risk Assessment: International Initiative for Risk Management Effectiveness. *Procedures of the 15th World Conference on Earthquake Engineering*. Lisbon, Portugal.

Cardona O, Ordaz M, Reinoso E, Yamín L, Barbat A (2010) Comprehensive Approach to Probabilistic Risk Assessment (CAPRA). International initiative for disaster risk management effectiveness. *Procedures of the 14th European conference on earthquake engineering*, Ohrid, Macedonia.

Carreño M. (2006) Técnicas innovadoras para la evaluación del riesgo sísmico y su gestión en centros urbanos: Acciones ex ante y ex post. Ph.D. Thesis, Universidad Politécnica de Cataluña, Barcelona, Spain.

Carreño M., Cardona O., Barbat A. (2007) Urban seismic risk evaluation: a holistic approach. *Natural Hazards*. 40(1): 137-172.

Carreño M., Cardona O., Barbat A. (2012) New methodology for urban seismic risk assessment from a holistic perspective. *Bulletin of earthqake engineering* 10(2): 547-565.

CIMNE, EAI, INGENIAR, ITEC (2013) Probabilistic modeling of natural risks at the global level: Global Risk Model. http://www.preventionweb.net/english/hyogo/gar/2013/en/home/documents.html Accessed on January 03, 2014.

Consorcio de Compensación de Seguros – CCS (2012). Estadística: Riesgos extraordinarios. Serie 1971-2012. http://www.consorseguros.es/web/c/document_library/get_file?uuid=548d4f59-b6c5-40dd-b06b-98dbcefd790f&groupId=10124. Accessed on December 20, 2013.

ESRI ArcMap (2010) Basemap imagery.

Evaluación de Riesgos Naturales América Latina - ERN-AL (2010) Comprehensive Approach to Probabilistic Risk Assessment, http://www.ecapra.org. Accessed on January 03, 2014.

German Research Center for Geosciences – GRCG (2010) Seismic Hazard Harmonization in Europe SHARE. Development of a common methodology and tools to evaluate earthquake hazard in Europe. Theme 6: Environment. German Research Center for Geosciences.

Grünthal G (1998) European Macroseismic Scale. Centre Européen de Géodynamique et de Séismologie.

Gutenberg R, Richter C.F (1944) Frequency of earthquakes in California. *Bulletin of the Seismological Society of America* 34:185-188.

Instituto Nacional de Estadística - INE (2011). Censo de población y vivienda 2011. http://www.ine.es/censos2011_datos/cen11_datos_res_pob.htm. Accesed on December 10, 2013.

Ministerio de Hacienda y Administración Pública – MHAP . (2013). Dirección General del Catastro. http://www.catastro.meh.es/. Accessed on September 15, 2013.

Miranda E. (1999). Approximate seismic lateral deformation demands in multistory buildings. *Journal of Structural Engineering* 125(4): 417-425.

Ordaz M, Aguilar A, Arboleda J, (2007) CRISIS 2007 V7.6, Program for computing seismic hazard. Instituto de Ingeniería. Universidad Nacional Autónoma de México.

Ordaz M (2000) Metodología para la evaluación del riesgo sísmico enfocada a la gerencia de seguros por terremoto. Universidad Nacional Autónoma de México, México D.F.

Ordaz M, Miranda E, Reinoso E, Pérez-Rocha L (1998) Seismic loss estimation model for Mexico City. *Procedures of the 12th World Conference on Earthquake Engineering*. Auckland, New Zealand.

Salgado M, Zuloaga D, Bernal G, Mora M, Cardona O (2013a) Fully probabilistic seismic risk assessment considering local site effects for the portfolio of buildings in Medellín, Colombia. *Bulletin of earthquake engineering* DOI: 10.1007/s10518-013-9550-4.

Salgado M, Zuloaga D, Cardona O (2013b) Evaluación probabilista del riesgo sísmico de Bogotá y Manizales con y sin la influencia de la Caldas Tear. *Revista de ingeniería* 38:6-13. Universidad de Los Andes, Bogotá, Colombia.

Torres M, Jaimes M, Reinoso E, Ordaz M (2013) Event-based approach for probabilistic flood risk assessment. *International journal of river basin management* DOI: 10.1080/15715124.2013.847844.

United Nations International Strategy for Disaster Risk Reduction-UNISDR (2013) Global Assessment Report on Disaster Risk Reduction 2013. Geneva, Switzerland.

Valcárcel J, Bernal G, Mora M (2012. Lorca earthquake May 11 2011: a comparison between disaster figures and risk assessment outcomes. *Procedures of the 15th World Conference on Earthquake Engineering*. Lisbon, Portugal.

Vargas Y, Pujades L, Barbat A, Hurtado J (2013a) Capacity, fragility and damage in reinforced concrete buildings: a probabilistic approach. *Bulletin of earthquake engineering* 11(6):2007-2032.

Vargas Y, Pujades L, Barbat A (2013b) Evaluación probabilista de la capacidad, fragilidad y daño sísmico en edificios de hormigón armado. *Revista internacional de métodos numéricos para cálculo. y diseño en ingeniería* 29(2):63-78.

Vargas Y, Barbat A, Pujades L, Hurtado J (2013c) Probabilistic seismic risk evaluation of reinforced concrete buildings. *Structures and buildings*. doi:10.1680/stub.12.00031.

Vielma J, Barbat A, Oller S (2010) Seismic safety of low ductility structures used in Spain. *Bulletin of earthquake engineering* 8(1):135-155.

Vielma J, Barbat A, Oller S (2009) Seismic performance of waffled-slab floor buildings. *Structures and buildings*. 162(SB3):169-182.