ADVANCES IN SEISMIC VULNERABILITY ASSESSMENT OF REINFORCED CONCRETE BUILDINGS APPLIED TO THE EXPERIENCE OF LORCA (SPAIN) 2011 EARTHQUAKE

J. L. RÓDENAS, A. TOMÁS & S. GARCÍA-AYLLÓN
Department of Civil Engineering, Universidad Politécnica de Cartagena (UPCT), Spain.

ABSTRACT

Despite the technical advances in seismic structural design, many regions still present a high level of seismic risk, principally due to the high vulnerability of their buildings. A modification of the empirical method for assessing the seismic vulnerability of reinforced concrete buildings in urban areas is proposed in this contribution. In the RISK-UE LM1 framework, the values of certain behaviour modifiers related to the typological, structural and urban parameters of the buildings have been modified according to a review and analysis of the currently available models and an evaluation of the actual seismic performance of buildings. This provides continuity to the progress of the previous works published to date. The proposal has been applied to the city of Lorca, Spain, for which ample knowledge of the damage occurred in the earthquake of May 11, 2011 is available. Less dispersion between actual observed and estimated damage in buildings is presented in comparison with the previous studies, with a statistical significance of 5%, thus achieving a more accurate evaluation of seismic risk. The new model also provides valuable information to be used in the planning and management of post-earthquake emergency situations when combining with GIS techniques, thus allowing for a better definition of several damage scenarios to enhance the development and urban preparedness in case of further seismic events.

Keywords: emergency management, empirical vulnerability assessment, observed damage, seismic vulnerability.

1 INTRODUCTION

Some of the most recent seismic disasters (L'Aquila 2009, Lorca 2011, Emilia Romagna 2012, Nepal 2015, Ecuador 2016, Amatrice 2016), have once again revealed the inadequate performance of many existing buildings against seismic action. This performance is observed not only in structures designed without seismic regulations – or with early versions of seismic codes –, but also in those designed with recent seismic codes.

Therefore, the analysis of the seismic behaviour of buildings continues to be one of the principal aims of Seismic Engineering [1, 2], not only from the perspective of the loss of human life and the physical damage originated in buildings, but also because of the damages caused by losses and inefficiencies in communication and services networks.

The seismic vulnerability of a structure can be defined as its intrinsic predisposition to damage at the occurrence of an earthquake of a certain severity [3]. This property, which is directly related to the design and construction characteristics of the building (structural typology, geometry, quality of the materials), therefore constitutes an internal factor, independent of the seismic action. Accordingly, seismic risk (the potential damage to a building, loss of human life and economic losses that may occur in a specified period of exposure) can be expressed as the convolution of vulnerability and seismic hazard (the probability of occurrence of a seismic event of certain severity in a specific site and during a determined period of exposure).

The availability of well-documented material on the damages caused by earthquakes (such as the Lorca earthquake in 2011), from on-site observations of the seismic effects as well as

ISSN: 2046-0546 (paper format), ISSN: 2046-0554 (online), http://www.witpress.com/journals
DOI: 10.2495/CMEM-V6-N5-887-898

from comparison with previously estimated damages, provides an opportunity to improve the empirical methodologies, which can help evaluate the seismic response of buildings in urban areas and decrease the level of uncertainty associated with seismic risks.

2 RISK-UE METHODOLOGIES FOR SEISMIC VULNERABILITY ASSESSMENT OF BUILDINGS

RISK-UE Project [4] stated two methodologies for the evaluation of the levels of seismic risk in urban areas. The first one, named as methodology LM1 or the Level I method and based on empirical research, characterizes the seismic hazard of the urban area in terms of macro-seismic intensity EMS-98, and the vulnerability of the buildings through a vulnerability index obtained according to the Vulnerability Index Method (VIM). The second one, known as methodology LM2 or the Level II method, considers the seismic action in terms of the corresponding spectrum of demand and the seismic vulnerability according to the capacity spectrum of the analysed structure [5].

With respect to empirical methods, the VIM constitutes a procedure that combines the vulnerability classes of the EMS-98 scale and the Italian method [6] for the characterization of the seismic vulnerability of buildings. This methodology is based on basic vulnerability indexes I_{v_t} that characterize the seismic behaviour of the most usual structural typologies in urban areas. These indexes are included in the BTM (Building Typology Matrix) [7] and are shown in Table 1 for several building typologies defined in the BTM and have been modified subsequently by Lagomarsino and Giovinazzi [5].

In addition, since the seismic behaviour of a certain building also depends on factors such as its grade of conservation or the level of seismic design code, as well as on other structural and urban planning parameters such as the number of storeys above ground, the geometric and stiffness regularity or the relative position of the building in the block, the LM1 methodology modifies this basic index of vulnerability I_{v-t} according to a series of values of penalty or improvement ΣM_C.

In this way, since the first version [7], a series of reviews have been developed in the definition and quantification of these behaviour modifiers [8–11], calibrating the influence of several dispositions (i.e. irregularity in plant or elevation, difference of height between nearby buildings, etc.), in the seismic performance of buildings.

Thus, the global vulnerability index of each building I_{v-b} can be evaluated through the following expression [9]:

$$I_{\mathrm{v-b}} = I_{\mathrm{v-t}} + \sum_{j=1}^{n} M_{\mathrm{Cj}} + \Delta M_R . \tag{1}$$

where I_{v-t} is the basic vulnerability index of the structural typology to which the building belongs (Table 1); ΣM_C are the different modifiers of behaviour that consider the structural and urban planning characteristics specifically for each building analysed; and ΔM_R is a

Table 1: Vulnerability indexes for RC building typologies defined in BTM [5, 7].

Typologies	Building type	I_v^{min}	I_v^-	I_v^*	I_v^+	I_v^{max}
RC1	Concrete moment frame	0.140	0.330	0.484	0.640	0.860
RC2	Concrete shear walls	0.140	0.210	0.384	0.510	0.700
RC3	Dual system	0.060	0.127	0.522	0.880	1.020

RC = Reinforced Concrete

regional modifier assigned depending on the characteristics and constructive dispositions specific to the zone of study, the seismic design codes, the date of construction, or the opinion of experts from actual observed damage.

Finally, to evaluate the level of seismic damage of every building, the LM1 method employed a semiempirical vulnerability function dependent on two parameters: the vulnerability index $I_{v\text{-}b}$, and the macroseismic intensity I in the EMS-98 scale [5]:

$$\mu_D = 2.5\left[1+\tanh\left(\frac{I+6.25\,I_{v\_b}-13.1}{Q}\right)\right]. \tag{2}$$

where Q is a ductility coefficient of value 2.3 for most of the building typologies of BTM [5], and μ_D is the mean damage grade defined in the EMS-98 scale for reinforced concrete (RC) buildings [12].

3 ADVANCES FOR EVALUATING THE SEISMIC VULNERABILITY OF REINFORCED CONCRETE BUILDINGS IN URBAN AREAS

The reviews proposed for the behaviour modifiers of the LM1 method [8–11], have focused principally on the analysis of those parameters related to the influence of diverse urban planning dispositions in the seismic response of the buildings, such as short columns and soft first storeys. Nevertheless, other parameters related to the level of the seismic design code that has been applied, or the influence of the natural period in the seismic response of the building need to be adjusted to the actual performance of RC buildings, in order to differentiate it from the behaviour of unreinforced masonry structures.

Thus, a proposal for the seismic vulnerability assessment of RC buildings according to the RISK-UE LM1 method is presented in this contribution, based on a thorough review of the current methods and on an analysis of the observed seismic performance of the buildings in recent earthquakes. This proposal provides continuity to the progress of previous works published to date. The modifiers proposed to obtain the vulnerability index $I_{v\text{-}b}$ are shown in Table 2.

Firstly, the modifiers related to the level of seismic design code and the construction characteristics have been revised. The modifiers defined in [8] have been adjusted according to the seismic response of buildings, since a worse performance is usually observed in the structures designed with older, and less accurate, seismic codes [13–15]. Thus, the modifier can adopt the values 0.16, 0.08 or 0.00:

a) 0.16: Case of pre-code buildings (designed without seismic regulations). In this type of buildings, the value of the modifier is based on the simultaneous met of the following considerations: (i) use of simplified analysis methods for the structure; (ii) the lack of seismic construction requirements and details for the structure; (iii) the lack of seismic construction requirements and details for the foundation; and (iv) the likely deficient condition and/or quality of materials.
b) 0.08: Case of low code buildings (designed with early versions of seismic codes). The incorporation of several seismic recommendations for the structure and foundation in the codes reduces this modifier from 0.16 to 0.08, since only the simplified analysis methods and the likely deficient condition and/or quality of materials are considered in this case.
c) 0.00: Case of medium code or high code buildings (designed with latter seismic codes). A value of 0.00 is assigned to this modifier because more accurate analytic methods have been employed and better condition and quality of materials have been used.

Table 2: Proposal for new values of modifiers for the RISK-UE LM1 method depending on the level of the seismic design code. A detailed explanation of each item is available in [9].

Behaviour modifiers		Seismic design code: Pre-code	Low code	Medium code	High code
Level of seismic and structural design code		0.16	0.08	0	0
Nº storeys above ground	0 to 3	0.04	0.04	0.04	0.04
	4 to 7	0	0	0	0
	≥ 8	–0.04	–0.04	–0.04	–0.04
Plant irregularity		0.04 (RC < 0.5) 0.02 (0.5 ≥ RC < 0.7)			
Irregularity in elevation		0.04 (d > 3) 0.02 (1 < d ≤ 3)			
Short column		0.08	0.08	0.08	0.08
Insufficient seismic structural joint		0.04	0.04	0.04	0
Slope of the ground		0.04	0.04	0.04	0.04
Relative position in the block of buildings	Intermediate	–0.04	–0.04	–0.04	–0.04
	Corner	0.04	0.04	0.04	0.04
	Full corner/Header	0.06	0.06	0.06	0.06
Relation with adjoining buildings		[–0.04, 0.04] f (relative height between buildings)			
Soft storey		0.2	0.2	0.2	0.2

In accordance with the considerations mentioned above, a categorization of the national seismic codes is required prior to the application of the method to any urban area. This modifier can therefore be obtained depending on the construction period of the building and the seismic code valid in that period, which can be known from the cadastral database.

Damage in low-rise buildings is generally identified with cracks in masonry infill walls at the ground floor and structural failures at the end of columns due to the higher stiffness of this type of structures [16, 17]. Therefore, the factor relating to the number of storeys above ground is assigned depending on the natural vibration frequency of the structure, which is represented in the response spectrums defined in the seismic codes. Thus, for low-rise buildings, whose fundamental natural vibration period is related to the top of response spectrums with constant acceleration, the vulnerability is penalized by increasing it by a value of 0.04. Conversely, for high-rise buildings, whose fundamental natural vibration period is related to the descent branch of acceleration in response spectrums, the vulnerability is diminished by a value of –0.04.

In practice, most of the buildings in urban areas, especially those placed on low-to-moderate seismicity regions, either have no seismic structural joint between buildings, or such a joint is not wide enough or has not been constructed properly. In this sense, cracks in masonry infill walls and even in structural elements can usually be observed in the joint between adjoining buildings [13, 16, 17]. Therefore, a penalty value of 0.04 has been conservatively considered, except for those buildings designed with a high-level code.

Thus, the proposed values enable to implement a more adjusted approach using cadastral survey information and making an on-site inspection of the evaluated zone, depending on the typological, structural and urban parameters of the buildings, similar to the methodology that has been performed in previous reviews of the RISK-UE LM1 method.

The two modifiers related to the typology of foundations and the conservation state of the building defined in the LM1 method are difficult to quantify in most cases. These parameters have been removed because they have already been considered in the modifier relating to the level of the seismic design code. Similarly, considering the definition of the modifier ΔM_R presented in eqn (1), it has also been removed from the evaluation of the vulnerability index $I_{v\text{-}b}$ because the aspects involved in the assessment have already been included in the different behaviour modifiers Mc. Thus, part of the uncertainty associated to the vulnerability assessment has been reduced and, moreover, the generalization of the proposal has been simplified by removing one parameter that requires calibration depending on the area analysed.

4 APPLICATION USING DAMAGE DATA FROM THE LORCA 2011 EARTHQUAKE

Although the earthquake on May 11, 2011 that struck Lorca had a moderate magnitude of 5.1 Mw, it finally caused several casualties (9 deaths and more than 300 injured) and important structural damage that meant that more than 10,000 people were unable to return to their houses [13, 14]. The earthquake was assigned with an EMS-98 intensity of VII in the main districts of the city [13, 14].

A field study to document the seismic behaviour in RC buildings damaged in the Lorca earthquake, 2011, was carried out by the Department of Civil Engineering of Universidad Politécnica de Cartagena. After a comparison and validation process from an initial sample of 1,050 buildings, 406 homogeneous cases were selected, after removing unusual data or those registers providing insufficient information.

The seismic damage and several urban characteristics that may influence the seismic structural response were registered. The collected data were divided into three blocks containing: (i) general data, such as the building typology or the address; (ii) the constructive features and urban configuration of the building, such as the presence of short columns or soft storeys; and (iii) the assessment of EMS-98 damage grade μ_D. In the second stage of the work, these data have been completed and compared with the cadastral data needed to obtain the aforementioned behaviour modifiers in the RISK-UE LM1 method, such as year of construction, number of storeys above ground, or aggregate building position.

Based on this input data, the observed damage in each building has been compared with the corresponding value from the LM1 method, according to the different reviews proposed in the literature. The construction period distribution of the buildings analysed, according to the Spanish seismic code, is shown in Table 3. The building typology RC1 (based on moment resistant RC frames of ordinary design with unreinforced masonry infill [7]) has been selected to obtain the vulnerability index. A similar categorization for the case of Spanish seismic codes has been used in [9, 11].

The EMS-98 damage grade μ_D observed in the buildings depending on the period of construction is shown in Fig. 1. Within the group of structures constructed prior to 1963, 40% presented high damage levels ($\mu_D = 3$), whereas this percentage decreased to 6.6% in the buildings constructed after 1996. On the contrary, only 6.7% of the buildings prior to 1963 presented a slight grade of damage ($\mu_D = 1$), whereas this percentage reached 39.6% in the more recently constructed buildings.

Table 3: Construction period distribution of the buildings analysed in Lorca according to the Spanish seismic code level.

Period of construction	Spanish seismic code	Code level	Number of buildings	Buildings %	BTM typology
Before 1963	-	Pre-code	45	11.1	RC1
1963–1970	Recommendation MV-101 (1962)	Pre-code	52	12.8	RC1
1971–1995	PGS-1 (1968) and PDS-1 (1974)	Low code	203	50.0	RC1
1996 until now	NCSE-1994 and NCSE-2002	Medium code	106	26.1	RC1

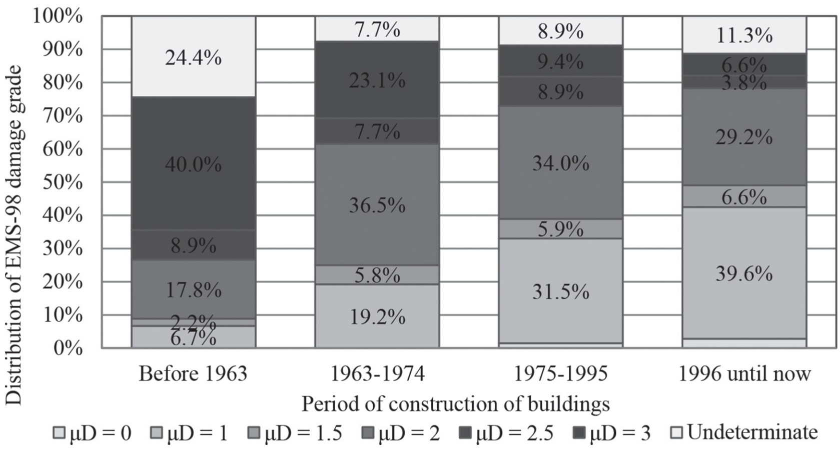

Figure 1: Distribution of EMS-98 mean damage grade observed on RC buildings after the Lorca earthquake, 2011, according to the period of construction.

The distribution of damage observed in different areas of Lorca after the 2011 earthquake is compared in Figs 2–6 with the calculated mean damage grade resulting from the RISK-UE LM1 method of [7] and the subsequent LM1 reviews of [8–11], respectively. For each building, the observed EMS-98 damage μ_D grade is plotted (as a cross mark) with its corresponding $I_{v\text{-}b}$ obtained from the respective LM1 version. Likewise, the simulated mean damage grades $\mu_D{}^*$ calculated from eqn (2) for an earthquake of EMS-98 intensity of VII and the same $I_{v\text{-}b}$ values are shown, along with the possible range $[\mu_D{}^-, \mu_D{}^+]$ associated with the interval $[I_v^-, I_v^+]$ defined in BTM (Table 1).

The high variability observed in the distribution of the cross marks is due to the behaviour modifiers considered by each author, which provide different $I_{v\text{-}b}$ values from the same building according to eqn (1). A wider range of $I_{v\text{-}b}$ values implies a better accuracy of the model, since a larger number of cases are considered. Anyway, the damage simulated by the LM1 method for RC buildings, and the subsequent revisions, is lower than the levels of the actual observed damage for an earthquake of EMS-98 intensity of VII. Therefore, these models would not totally represent the seismic behaviour of this type of buildings.

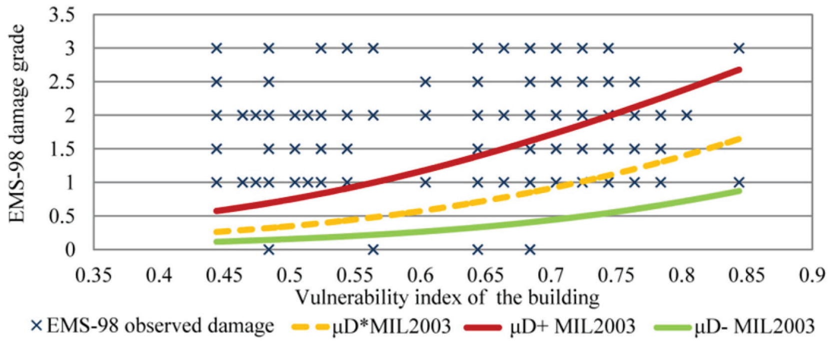

Figure 2: Comparison between EMS-98 observed damage on RC buildings from the Lorca earthquake, 2011, and the mean damage grade obtained from the RISK-UE LM1 method ([7], defined as MIL03), for an $I_{EMS\text{-}98}$ = VII earthquake, where μ_D* is the representative mean damage value, and [μ_D^-,μ_D^+] the possible range of the estimated mean damage grade.

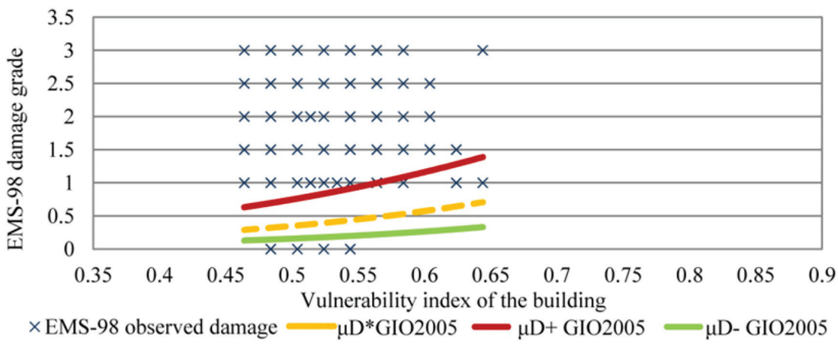

Figure 3: Comparison between EMS-98 observed damage on RC buildings from the Lorca earthquake, 2011, and the mean damage grade obtained from the revised RISK-UE LM1 method ([8], defined as GIO05), for an $I_{EMS\text{-}98}$ = VII earthquake, where μ_D* is the representative mean damage value, and [μ_D^-,μ_D^+] the possible range of the estimated mean damage grade.

Finally, the comparison between the mean damage grade obtained according to the improved method and its correspondence with the observed damage is shown in Fig. 7. A better correlation between observed and simulated damage is appreciated, with a greater number of observations included within the range of probable values of the method.

In order to analyse the significance level of the results and determine the adjustment quality of the calculated damage, a new variable $Z_i = OD_i - \mu D_i$ has been defined, where OD_i is the EMS-98 observed damage for every building i, and μD_i is the corresponding mean damage grade obtained according to the different reviews of the LM1 method. In addition, the difference $Z_{ij} - Z_{i\_PRO}$ has been evaluated, where Z_{ij} is the value of the previous difference for the building i obtained from a certain review j of the LM1 method and Z_{i_PRO} is the value for the building i obtained from the new proposal.

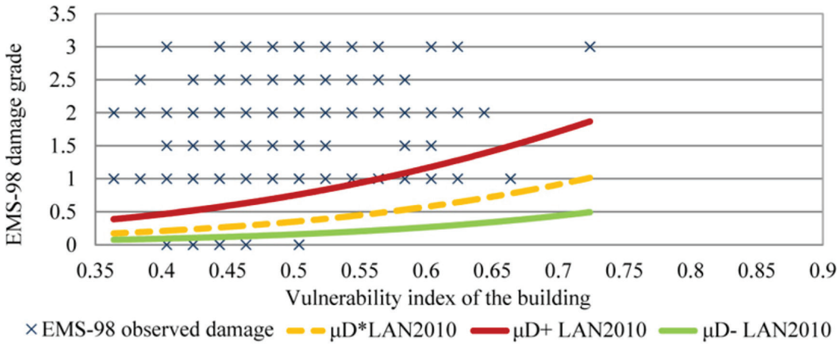

Figure 4: Comparison between EMS-98 observed damage on RC buildings from the Lorca earthquake, 2011, and the mean damage grade obtained from the revised RISK-UE LM1 method ([9], defined as LAN10), for an $I_{EMS\text{-}98}$ = VII earthquake, where μ_D* is the representative mean damage value, and $[\mu_D^-,\mu_D^+]$ the possible range of the estimated mean damage grade.

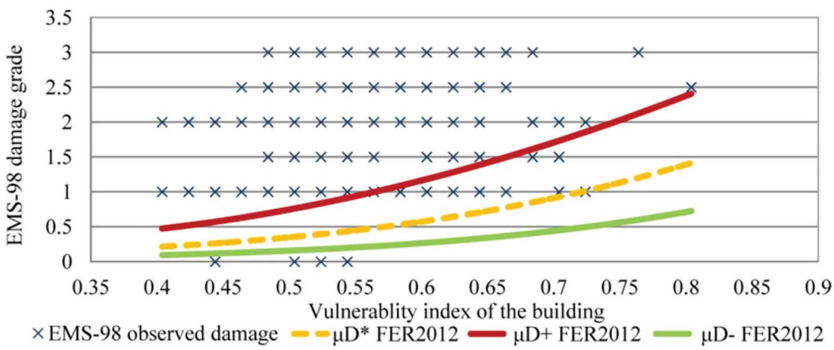

Figure 5: Comparison between EMS-98 observed damage on RC buildings from the Lorca earthquake, 2011, the mean damage grade obtained from the revised RISK-UE LM1 method ([12], defined as FER12), for an $I_{EMS\text{-}98}$ = VII earthquake, where μ_D* is the representative mean damage value, and $[\mu_D^-,\mu_D^+]$ the possible range of the estimated mean damage grade.

When comparing the measures of central tendency and dispersion of the difference Z_{ij} - Z_{i_PRO}, some asymmetry arises in the distribution of the obtained data (Table 4). Consequently, a non-parametric Wilcoxon Signed-Rank Test for Paired Samples has been performed. For each of the different revisions of the LM1 method, a null hypothesis of equality of medians in the Z_{ij} - Z_{i_PRO} difference has been formulated. It implies that a significant difference would not be identified between the dispersion among observed and estimated damage obtained from the *j* review of the LM1 method and the dispersion obtained from the proposed model, for the case of the Lorca earthquake.

Thus, the median of the difference between observed and estimated damage obtained according to the proposed model would be less than the median obtained according to the currently available models of the LM1 method. By means of the value of the statistical parameter Z_{cal} – which follows a normal distribution according to the test methodology – the

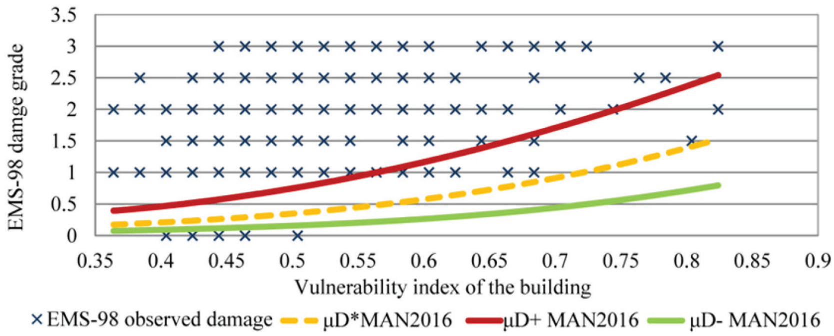

Figure 6: Comparison between EMS-98 observed damage on RC buildings from the Lorca earthquake, 2011, and the mean damage grade obtained from the revised RISK-UE LM1 method ([11], defined as MAN16), for an $I_{EMS\text{-}98}$ = VII earthquake, where μ_D* is the representative mean damage value, and [μ_D^-,μ_D^+] the possible range of the estimated mean damage grade.

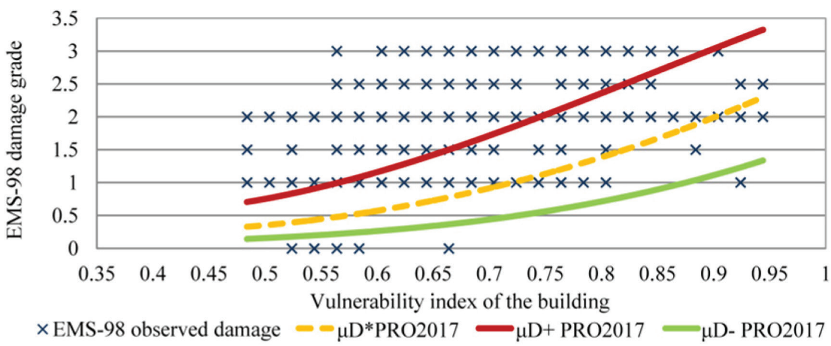

Figure 7: Comparison between EMS-98 observed damage on RC buildings from the Lorca earthquake, 2011, and the mean damage grade obtained from the proposed RISK-UE LM1 model (defined as PRO17), for an $I_{EMS\text{-}98}$ = VII earthquake, where μ_D* is the representative mean damage value, and [μ_D^-,μ_D^+] the possible range of the estimated mean damage grade.

Table 4: Central tendency measures of the difference Z_{ij} - Z_{i_PRO} comparing the proposed model with the current available review methods.

	MIL-03-PRO-17	GIO-05-PRO-17	LAN-10-PRO-17	FER-12-PRO-17	MAN-16-PRO-17
Sample mean	0.247	0.478	0.426	0.200	0.288
Sample standard dev.	0.367	0.378	0.382	0.285	0.249
Sample median	0.165	0.384	0.324	0.159	0.238

p-value can be obtained. With a p-value < 0.05, the null hypothesis of equality of medians is refuted for a statistical significance level of $\alpha = 0.05$ for each model (Table 5). Therefore, less dispersion between observed and estimated damage would be observed in comparison with the difference obtained according to the current reviews of the method, for the case of RC buildings analysed in Lorca.

The visualization of vulnerability indexes and expected damage by using GIS techniques from a geo-referencing process enables to identify the most vulnerable areas of the city and the planning and management of the different post-earthquake emergency situations. The geospatial distribution of the vulnerability indexes of RC buildings analysed in Lorca, obtained from the model of LM1 methodology proposed in this contribution, is shown in

Table 5: Development of Wilcoxon Signed-Rank Test for Paired Samples. *T* and *Zcal* correspond to statistical variables defined in the test methodology.

	MIL-03-PRO-17	GIO-05-PRO-17	LAN-10-PRO-1	FER-12-PRO-1	MAN-16-PRO-1
T=min$(T+,T-)$	11,071	159	2,070	7,501	1,550
Zcal	−10.89	−16.29	−15.42	−11.55	−14,99
$Z\alpha$ (One tail)	−1.64	−1.64	−1.64	−1.64	−1.64
p-value	0.000	0.000	0.000	0.000	0.000

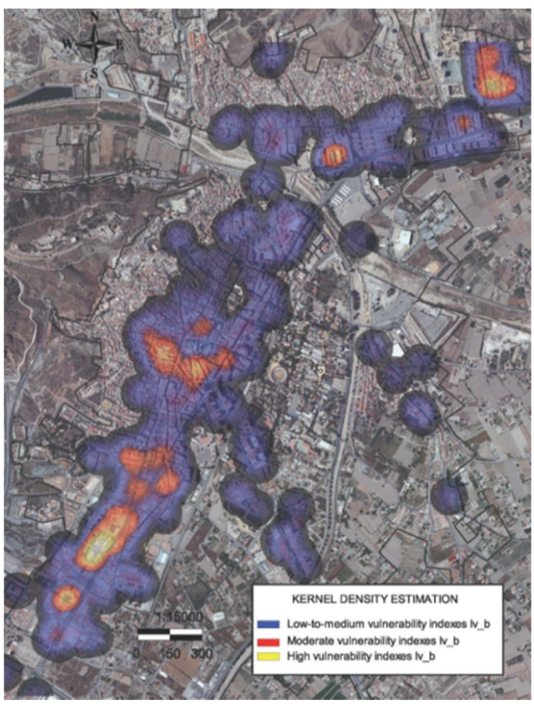

Figure 8: Kernel density estimation plot of the vulnerability indexes I_{v_b} of RC buildings analysed in the city of Lorca, obtained according to the proposed LM1 model.

Fig. 8, where a Kernel density estimation has been used. In the case of Lorca, the modelled damage reflects that the areas most vulnerable are mainly concentrated in the northeast, the central and the southwestern neighbourhoods of the city.

5 CONCLUSIONS

This article proposes to modify the empirical method of seismic vulnerability assessment in urban areas. In the RISK-UE LM1 framework, the behaviour modifiers related to the level of seismic code design, the number of storeys above ground, and the structural joint between adjoining buildings have been modified according to a review of the currently available models of LM1 methodology and an evaluation of the actual seismic performance of buildings.

This proposal provides continuity to the progress of the previous works published to date, simplifying the application of the methodology to any urban area. It can be implemented from cadastral information and an on-site inspection of the evaluated zone. The generalization of the proposal has been simplified by removing one parameter – the regional modifier – that requires calibration depending on the area analysed.

A better correspondence between mean damage grades estimated in RC buildings and the corresponding actual observed data reported from the Lorca (Spain) earthquake, 2011 is identified, with a significance level of 5%, thereby reducing the level of uncertainties associated with this type of methodology and providing a more accurate evaluation of seismic risk.

Despite the fact that such comparisons can hardly provide the basis for validation of an earthquake loss model, the observed tendency shows that the damage simulated by different methods remains below the actual observed damage in most cases, so the definition of the expected losses scenarios is not totally adequate. The existence of well-documented material on the damages caused by earthquakes (such as the Lorca earthquake in 2011), which does not happen too often, provides an opportunity to improve the methodologies of vulnerability assessment and help evaluate the seismic risk of buildings in urban areas.

By using GIS techniques, the proposal also enables for better planning and management of post-earthquake situations, characterizing the different damage scenarios more precisely.

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