Seismic vulnerability and damage assessment in Navarre (NE Spain)

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ABSTRACT:
A regional characterization of the seismic vulnerability of the building stock of Navarre (Northern Spain) and the expected damage associated with expected ground shaking for a 475-year return period is presented. Besides the initial planning meetings, the work consists on three phases: The first is the field work conducted along different routes crossing the entire region, including main cities. Two geographical areas with distinctive construction patterns and characteristic typologies were recognised and delimited, together with a transition zone. Several buildings were sampled and documented, and empirical vulnerability distributions were obtained. The second phase relates to cadastral data exploitation and processing, selection of parcels as working units and selection of municipalities and districts as representation units. Based on the age of construction and the associated seismic code requirements; the number of stories; and the empirical distributions derived in the earlier stage, statistical distributions of building vulnerability classes were composed following three vulnerability classifications. These include the vulnerability classification of the European Macroseismic Scale, the vulnerability index approach and the Hazus classification. This phase was as important as time-consuming, and set the basis for the proper development of the subsequent analyses. The third phase consisted on calculating the expected damage with empirical as well as with analytical methods, using as seismic input an updated hazard-consistent seismic intensity map of the region. Vulnerability and damage results derived with the three methods used are compared and analysed, and their suitability discussed. Results of this work will be used in the regional seismic risk plan of Navarre (RISNA Project).

Keywords: vulnerability, damage, Spain, EMS 98, vulnerability index, capacity spectrum

1. INTRODUCTION AND OBJECTIVES

The assessment of seismic risk at a regional scale requires estimating the seismic vulnerability of a building stock that is too large as to make in situ (building by building) recognitions in a reasonable time period. Alternative approaches that combine the knowledge of prevailing building typologies in the study region with informed statistical estimates of the geographical distribution of common constructive techniques turn out to be reasonably good solutions to this difficulty.

Additionally, the relation between seismic ground motion and structural damage cannot be established (with local data) in areas of relatively low seismic activity for the full range of expected ground motions and building classes. Thus, the expected damage has to be estimated either from empirical data observed in other areas with similar structural typologies, either through analytical methods relating seismic demand with structural capacity and fragility.

In this work, three methods for regional vulnerability estimation and mean damage assessment are considered. They are based on the European Macroseismic Scale EMS 98 classification (Grünthal, G. 1998), on the vulnerability index approach (RISK-UE level 1 method, Milutinovic and Trendafiloski, 2003) and on the Hazus classification (originally based on FEMA 178). The focus is placed on dwelling structures and results are representative for the entire municipality (although the calculation unit was smaller as it was a combination of municipality and zip code). The parameters considered as input ground motion are the macroseismic intensity (the first two methods) and the peak ground acceleration (for the third one). The actual values used in the calculations refer to expected estimates (for the 475-year return period) and averaged estimates over the built area of each municipality (Figure 1).These values are taken from the RISNA Project, aimed at the development of a seismic risk analysis that constitutes the basis for the design of emergency plans by the Emergency Agency of Navarre (Benito et al., 2008).

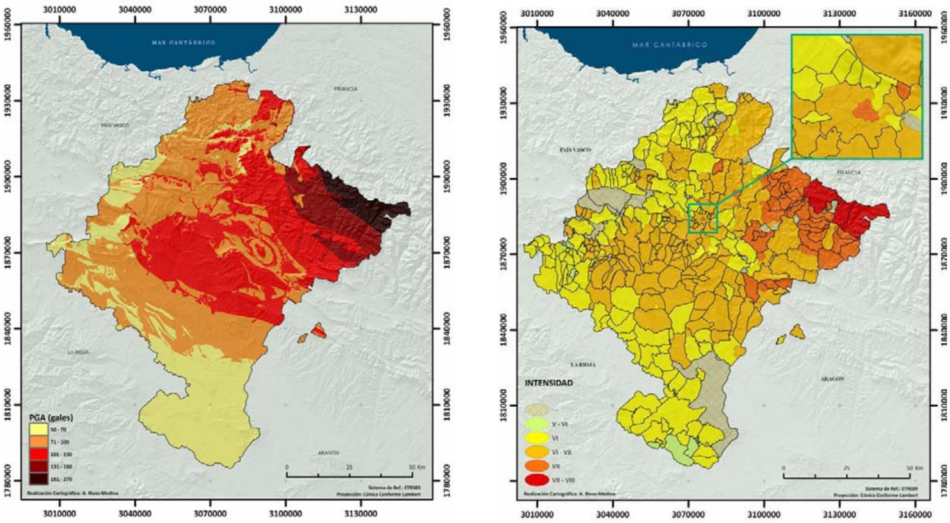

Figure 1. Expected ground motion for the 475-year return period in Navarre (RISNA Project, Benito et al., 2008): Left: peak ground acceleration (including site effects). Right: EMS intensity.

2. BUILDING TYPOLOGIES IN NAVARRE

Navarre has many consolidated historical cities of important architectural heritage. For the sake of a vulnerability analysis it is useful to divide the building stock into two large groups: traditional construction, where there is an accidental earthquake resistant design (ERD) based on the characteristics of the structural type, and engineered construction, where structures perform to seismic forces defined in a mandatory code. Mandatory codes defining seismic loads exist in Spain since 1962. This is a useful date to chronologically divide traditional (pre-1962) and engineered (post-1962) structures. Modern engineered structures tend to perform to well known building types and housing formats that smooth out regional differences in favour of standardized solutions, but the traditional building stock shows considerable regional differences.

The building stock was thoroughly analysed in two field surveys throughout the region carried out by the architectural team between March and May 2008. Two routes were chosen that cross the region North to South including all major towns. The architectural team noted main features in terms of building age, structural composition, number of floors and basic geometry for those buildings considered to be representative of both traditional and engineered structures for each location. Naturally, each and every structure has unique characteristics, but for the sake of a vulnerability assessment, these have to be assimilated to a limited number of building types. For this exercise, a total of 9 basic building types were identified and drawn up for the region, comprised of 4 basic traditional types, and 5 basic engineered building types (Table 1). A code was assigned to each type, and a basic 3D model was drawn up to better represent the characteristics of each type.

Navarre straddles two large Iberian climatic regions: Dry Iberia towards the south in the Ebro basin and Humid Iberia towards north, in the Pyrenees range; and these regional differences can be seen in the composition of the traditional building stock. In general terms, simple stone masonry is prevalent in the traditional construction of the northern mountainous area. In the southern sedimentary basins of the south of the region, fieldstone rubble masonry is also widespread but commonly found alongside brick masonry structures and a smaller amount of adobe buildings. The urban environment was found to be more homogeneous, with unreinforced brick masonry comprising the main urban fabric of traditional construction throughout the region. Modern engineered buildings since the mid 20th century tend to smooth out regional differences, as construction practices become standardized and technical codes become widespread. Reinforced Concrete frames, with masonry partitions and envelopes are by far the dominant building type in recent decades, even for small-scale housing.

Figure 2: Examples of traditional (left) and engineered (right) building types in Navarre and their vulnerability assessment.

Table 1. Building classification of Navarre based on field surveys. Equivalences with representative building types of EMS98, Iv and Hazus vulnerability classifications are provided (Iv values include regional and behaviour modifiers).

Name	Description	EMS 98	Iv	Hazus
MPFM	Fieldstone masonry with no diaphragm action	A	0.88	URM
MAFM	Adobe masonry with no diaphragm action	A	0.88	URM
MLFM	Brick masonry with no diaphragm action	B	0.74	URM
MLFH	Brick masonry with diaphragm action	B	0.65	RM
HPAL	Reinforced concrete frame with masonry infill panels	C	0.64	C3
HPL	Reinforced concrete frame	D	0.54	C1
HPT	Concrete shear wall	D	0.38	C2
M	Steel frame structures	D	0.52	S5
P	Prefabricated structures	C	0.54	PC2

3. VULNERABILITY ASSESSMENT

The 9 basic building types defined for Navarre are sorted according to three widely cited approaches; the EMS98 scale, the RISK UE Vulnerability Index method, and the US FEMA 178 code. A combination of cadastral information (land use, number of floors, location and construction age), renovation dates of seismic code prescriptions, and results of the field survey are used to characterise the seismic vulnerability of the building stock of Navarre.

The regional cadastre database contains detailed information regarding location, number of floors, age and building use for all buildings registered in Navarre, but no information regarding the structural type of the building. This information had to be therefore estimated and assigned to one of the 9 basic structural types identified during the field survey. To this effect, the cadastre database was organised into 6 building use types; public buildings; commercial and office buildings; industrial; rural detached or semi detached housing; urban detached or semi detached housing; and dense town housing. For each use a transfer matrix was drawn up to assign one or more of the 9 basic structural types based on the information gathered by the architectural team during the surveys and the chronological distribution of the building stock (Table2).

Table 2. Vulnerability transfer matrices.

Matriz de transferencia para tipos 1 - publicos, sanitarios, docentes y especiales

		Edad de construcción																				
		1920			1921 - 1940			1941 - 1964			1965 - 1976			1977 - 1996			1997 - 2004			2005 - 2006		
		FEMA-178	I_V	EMS 98	FEMA-178	I_V	EMS 98	FEMA-178	I_V	EMS 98	FEMA-178	I_V	EMS 98	FEMA-178	I_V	EMS 98	FEMA-178	I_V	EMS 98	FEMA-178	I_V	EMS 98
plantas	-2	34-URML	0,74	B	34-URML	0,74	B	29-RM1L	0,63	C	29-RM1L	0,63	C	22-C3L	0,6	C	22-C3L	0,51	C	22-C3L	0,51	C
	3,7	35-URMM	0,78	B	35-URMM	0,78	B	30-RM2M	0,65	C	30-RM2M	0,65	C	23-C3M	0,64	C	23-C3M	0,55	C	23-C3M	0,55	C
	8+	35-URMM	0,78	B	35-URMM	0,78	B	24-C3H	0,72	C	24-C3H	0,72	C	24-C3H	0,72	C	24-C3H	0,63	C	24-C3H	0,63	C

Matriz de transferencia para tipos 2 - comercial y administrativo

		Edad de construcción																				
		1920			1921 - 1940			1941 - 1964			1965 - 1976			1977 - 1996			1997 - 2004			2005 - 2006		
		FEMA-178	I_V	EMS 98	FEMA-178	I_V	EMS 98	FEMA-178	I_V	EMS 98	FEMA-178	I_V	EMS 98	FEMA-178	I_V	EMS 98	FEMA-178	I_V	EMS 98	FEMA-178	I_V	EMS 98
plantas	-2	34-URML	0,74	B	34-URML	0,74	B	29-RM1L	0,63	C	22-C3L	0,6	C	22-C3L	0,6	C	16-C1L	0,48	D	16-C1L	0,48	D
	3,7	35-URMM	0,78	B	35-URMM	0,78	B	30-RM2M	0,65	C	23-C3M	0,64	C	23-C3M	0,64	C	17-C1M	0,52	D	17-C1M	0,52	D
	8+	35-URMM	0,78	B	35-URMM	0,78	B	24-C3H	0,72	C	24-C3H	0,72	C	24-C3H	0,72	C	18-C1H	0,58	D	18-C1H	0,58	D

Matriz de transferencia para tipos 3 - industrial y deportivo

		Edad de construcción																				
		1920			1921 - 1940			1941 - 1964			1965 - 1976			1977 - 1996			1997 - 2004			2005 - 2006		
		FEMA-178	I_V	EMS 98	FEMA-178	I_V	EMS 98	FEMA-178	I_V	EMS 98	FEMA-178	I_V	EMS 98	FEMA-178	I_V	EMS 98	FEMA-178	I_V	EMS 98	FEMA-178	I_V	EMS 98
plantas	todas	34-URML	0,74	B	34-URML	0,74	B	29-RM1L	0,63	C	13-S5L	0,52	D	13-S5L	0,52	D	13-S5L	0,52	D	13-S5L	0,52	D

Matriz de transferencia para tipos 4 - Residencial 1 (RURAL)

		Edad de construcción																				
		1920			1921 - 1940			1941 - 1964			1965 - 1976			1977 - 1996			1997 - 2004			2005 - 2006		
		FEMA-178	I_V	EMS 98	FEMA-178	I_V	EMS 98	FEMA-178	I_V	EMS 98	FEMA-178	I_V	EMS 98	FEMA-178	I_V	EMS 98	FEMA-178	I_V	EMS 98	FEMA-178	I_V	EMS 98
plantas	-2	34-URML	0,88	A	34-URML	0,88	A	34-URML	0,88	A	34-URML	0,88	A	34-URML	0,74	B	34-URML	0,74	B	34-URML	0,74	B
	3+	35-URMM	0,92	A	35-URMM	0,92	A	35-URMM	0,92	A	35-URMM	0,92	A	35-URMM	0,78	B	35-URMM	0,78	B	35-URMM	0,78	B

Matriz de transferencia para tipos 5 - Residencial 2 (urbana)

		Edad de construcción																				
		1920			1921 - 1940			1941 - 1964			1965 - 1976			1977 - 1996			1997 - 2004			2005 - 2006		
		FEMA-178	I_V	EMS 98	FEMA-178	I_V	EMS 98	FEMA-178	I_V	EMS 98	FEMA-178	I_V	EMS 98	FEMA-178	I_V	EMS 98	FEMA-178	I_V	EMS 98	FEMA-178	I_V	EMS 98
plantas	-2	34-URML	0,88	A	34-URML	0,74	B	34-URML	0,74	B	29-RM1L	0,63	C	29-RM1L	0,63	C	22-C3L	0,51	C	22-C3L	0,51	C
	3+	35-URMM	0,92	A	35-URMM	0,78	B	35-URMM	0,78	B	30-RM2M	0,65	C	30-RM2M	0,65	C	23-C3M	0,55	C	23-C3M	0,55	C

Matriz de transferencia para tipos 6 - Residencial 3 Colectiva

		Edad de construcción																				
		1920			1921 - 1940			1941 - 1964			1965 - 1976			1977 - 1996			1997 - 2004			2005 - 2006		
		FEMA-178	I_V	EMS 98	FEMA-178	I_V	EMS 98	FEMA-178	I_V	EMS 98	FEMA-178	I_V	EMS 98	FEMA-178	I_V	EMS 98	FEMA-178	I_V	EMS 98	FEMA-178	I_V	EMS 98
plantas	-2	34-URML	0,74	B	34-URML	0,74	B	29-RM1L	0,63	C	22-C3L	0,6	C	22-C3L	0,6	C	22-C3L	0,51	C	22-C3L	0,51	C
	3,7	35-URMM	0,78	B	35-URMM	0,78	B	30-RM2M	0,65	C	23-C3M	0,64	C	23-C3M	0,64	C	23-C3M	0,55	C	23-C3M	0,55	C
	8+	35-URMM	0,78	B	35-URMM	0,78	B	24-C3H	0,72	C	24-C3H	0,72	C	24-C3H	0,72	C	24-C3H	0,63	C	24-C3H	0,63	C

The chronological ordering of the database allowed to discern between traditional and engineered buildings and to evaluate the effect of different code time windows, providing higher confidence and accuracy in the assignment of vulnerability. For traditional structures until about 1950, this process is straightforward, but for engineered structures after 1962, the provisions of each building code in effect in Navarre since that date had to be taken into account. There have been five national code revisions, and associated hazard maps have varied in the values given to different part of the region over time. In all cases the values are moderate. According to the latest seismic code NCSE 02 (2002), earthquake-resistant design is mandatory for approximately the northern third of the region, with expected PGA values below 0.04 g for the return period of 500 years. Such low values (in combination with other conditions) effectively imply that earthquake loads may be ignored for regular reinforced concrete structures. The contemporary engineered building stock is therefore assumed to perform to low code conditions as defined by the US FEMA 178 code and the RISK UE Vulnerability Index guide.

The results of the vulnerability distribution for Navarre were portrayed onto maps and analysed to a Postal Code area detail. Regarding traditional building types, a large percent over the whole of highly vulnerable structures are found in the northern mountainous counties of the region, but their absolute number is rather small in this sparsely populated area (Figure 3). On the other hand, a larger number of vulnerable structures, but representing a smaller percentage over the whole, are to be found in the densely populated southern half of the region. Regarding engineered structures, the larger towns in the region house the larger number and higher proportion of modern and less vulnerable structures.

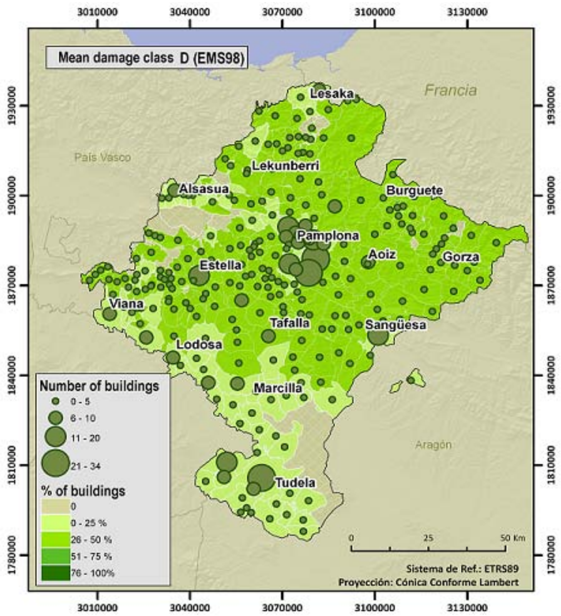

Figure 3. Distribution of vulnerability D buildings in Navarre in absolute and relative numbers.

Additionally, an average municipal vulnerability distribution may be obtained by grouping the number of buildings corresponding to high, medium and low vulnerability classes (Figure 4). This figure portrays the high incidence of high vulnerabilities in the northern part of the region and the concentration of low vulnerability building stocks in very concrete municipalities, corresponding to recent urban developments.

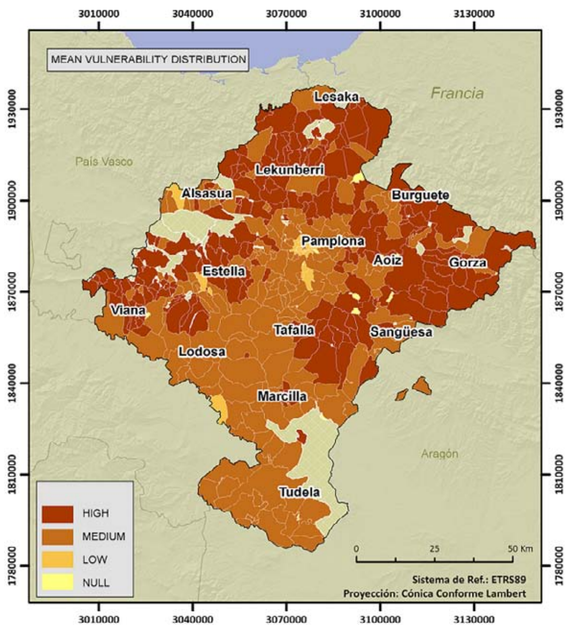

Figure 4. EMS-98 mean vulnerability distribution in Navarre.

4. DAMAGE ASSESSMENT

Three methods for expected damage estimation were used in consonance with the approaches used to vulnerability classification of the Navarrean building stock. These include: (1) data-based damage probability matrices (DPM) relating expected damage degrees to given intensity levels for the building vulnerability distribution in terms of the EMS 98 classification; (2) damage distribution associated to different vulnerability indexes associated to given intensity levels (RISK UE Level 1 approach); and (3) the capacity/demand spectrum approach implemented in Hazus (FEMA 178).

For each method, mean damage estimates for each municipality are calculated through the Eqn. 4.1:

$$\text{Mean damage} = \Sigma\, d_i \cdot n_i \qquad (4.1)$$

where d_i represents a damage degree (from 1 to 5) and n_i represents the number of buildings with expected damage d_i divided by the total number of buildings in the municipality. An example of expected mean damage distribution for the municipalities of Navarre following the damage probability matrices method is presented in Figure 5. Note that damage is relatively low (below 3 in the region). The municipalities with high mean damage concentrate in the northeastern part of the region, where relatively high ground motions are expected and a relatively large percentage of highly vulnerable buildings exist.

Similar geographical distribution patterns are observed using the other methods for estimating expected damage: the areas with higher and lower expected damage basically coincide using any of the three methods. By contrast, the absolute expected damage estimates provided by the three methods used in this study differ for a given municipality Overall, the vulnerability index method provides similar results that the DPM method (Iv slightly lower estimates). However, the Hazus-based method consistently predicts notably higher damage estimates than the other two methods (over 1 damage degree, Figure 6). This confirms again the limitations of applying the damage estimation approach implemented in Hazus directly to European building typologies.

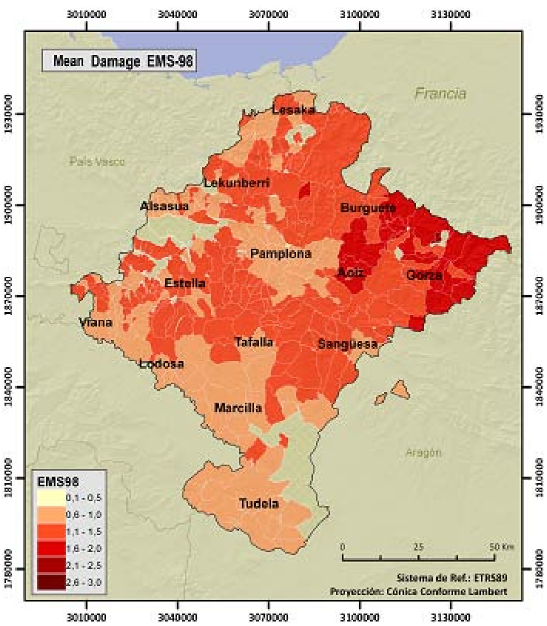

Figure 5. Mean damage distribution in Navarre (DPM method).

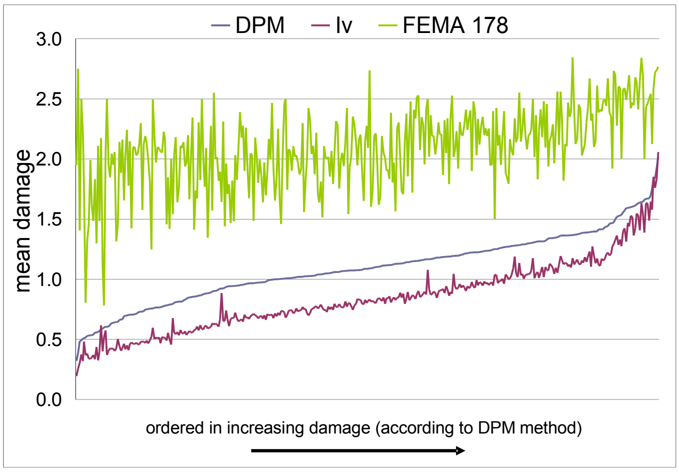

Figure 5. Mean damage for each municipality of Navarre estimated by the three methods considered in this work, ordered in increasing mean damage as resulting from the DPM method.

6. CONCLUSIONS

The combination of field surveys with statistical data and the temporal distribution of seismic code stipulations constitutes a useful approach to assess the seismic vulnerability of an entire region. The task of relating this regional vulnerability assessment to internationally known vulnerability classifications requires making approximations that may imply certain limitations, especially when transferring such distributions to expected damage estimates.

For the case study of Navarre, seismic hazard, seismic vulnerability and expected mean damage are larger in the northeastern part of the region than in the southern part. Expected mean damage is relatively low, never reaching values above damage degree 3.

Differences in the results are clear, especially between the empirical methods (DPM and Iv) in one hand, and the analytical method, in the other hand. Two main factors may explain these differences: the vulnerability classification (strongly based on European and American building typologies, respectively) and the different ground motion parameter used (intensity and a response spectrum anchored to peak ground acceleration values, respectively).

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