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Preliminary seismic risk assessment for Catalonia (Spain)

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ABSTRACT: Following Spanish regulations for Civil Defence, the Civil Defence Agency of the Catalan government has promoted an evaluation of the seismic risk in Catalonia. The final aim of this assessment is to provide the necessary information for establishing emergency plans in order to reduce the damage caused by future earthquakes. An estimation of vulnerability of dwelling buildings is carried out together with the assessment of seismic risk for people and of earthquake losses in all municipalities of Catalonia. The methodology developed is summarized in four steps: 1) Classification of the existing buildings in vulnerability classes according to EMS-92, 2) estimation of damage in buildings, 3) assessment of the human casualties, and 4) evaluation of economical losses. GIS representation is used in each step.

1 INTRODUCTION

Catalonia, located in the Northeastern part of Spain, is considered a region of low-to-moderate seismicity (intensity VI-VIII MSK for a 500 year return period) for which, according to Spanish regulation, seismic emergency plans, at local and regional level, should be prepared. Thus, the Civil Defence Agency of the Catalan government promoted in 1997 an investigation on the seismic risk, extended to all Catalan municipalities. The study started with the analysis of the most recent building's inventory available (the census of 1990 prepared by the Catalan Institution of Statistics) in order to derive vulnerability functions applicable to all buildings in the region (a total of nearl 935000, for a population of approximately 6.1 million inhabitants).

In addition to the information provided by the census, data on the state of preservation of buildings and the opinion of experts were considered to obtain such functions, which served to estimate the seismic risk derived from direct damage to buildings. The methodology involved in this process is similar to that used in studies carried out in the United States (ATC-13, 1985), Italy (Bramerini et al., 1995), Colombia (Ingeominas, 1997), Guadalupe (Martin et al., 1997), and other countries. The specific assumptions considered in our analysis are described in the following paragraphs.

2 CLASSIFICATION OF BUILDINGS IN VULNERABILITY CLASSES

A first task of the study was to classify all buildings of Catalonia in vulnerability classes, which, for our purpose, are those defined in the EMS-92. The elements considered for this classification are: age, height and zone of location (all of them given by the building census of 1990); structural typology and state of preservation (information obtained through a study carried out over a representative sample of the building population); and the opinion of experts.

With respect of the first three elements (those given by the census), buildings are grouped in 3 age classes, that comprise, respectively, those built before 1950, between 1950 and 1970 and after 1970; a classification that responds to the historical evolution of construction practice (Mañà, personal communication). Similarly, buildings have been classifyed by height in three ranges, low (up to 12 m), medium (15 m) and high (≥18); and location in two groups, urban and rural areas.

These subdivisions reflect on the one hand the difference of capacity of buildings of different height, and, in the other, the dependence, in general terms, of construction quality on the site location. Table 1 shows the final distribution of buildings according to these three parameters.

Table 1. Distribution of buildings in Catalonia by height, age and location.

Catalonia	Date of Construction					
	Pre-1950		1951-1970		Post-1970	
Height	Zone of Placement		Zone of Placement		Zone of Placement	
	Urban	Rural	Urban	Rural	Urban	Rural
≤ 12 m	232740	31119	212070	16304	315504	37346
= 15 m	7065	9	14083	24	11937	22
≥ 18 m	12699	2	21963	33	22028	44

With regard to structural typology, buildings of unreinforced masonry with concrete floors predominate in Catalonia. Adobe constructions represent an important percentage of buildings of the first age group, while constructions which reinforced concrete structure, introduced around 1970, cover some 25% of the total building population.

The *Direcció General d'Arquitectura i Habitatge* carried out a study on a representative sample of Catalonia buildings with the aim of analysing the state of preservation of all buildings in the region. The results of this study (together with the distribution shown in table 1) were very useful in the analysis developed by a group of experts to estimate the percentage of buildings, from all Catalonia, that could be included in each of the four vulnerability classes described in the EMS-92.

The values obtained from such percentages, for the groups considered in Table 1, are shown in table 2.

A summary of the table is also presented in figure 1; it can be seen that, from a total of 934992 buildings, 9% belong to class A, 40% to class B, 45% to class C and 6% (the smallest amount) to class D.

Table 2. Classification of buildings in Catalonia in vulnerability classes according to EMS-92.

Code of	Date of Construction					
Town	Pre-1950		1951-1970		Post-1970	
Height	Zone of Placement		Zone of Placement		Zone of Placement	
	Urban	Rural	Urban	Rural	Urban	Rural
≤ 12 m	20A+80B	30A+70B	5A+50B+45C	15A+70B+15C	85C+15D	5A+20B+65C+10D
= 15 m	20A+80B	40A+60B	10A+60B+30C	20A+70B+10C	5A+20B+65C+10D	10A+30B+55C+5D
≥ 15 m	40A+60B	60A+40B	15A+70B+15C	30A+65B+5C	8A+27B+60C+5D	15A+45B+40C

Numbers on table indicate percentage of buildings assumed at each vulnerability class.

Similar analysis has been carried out for every municipality of Catalonia, and its result is shown in figure 2. Some conclusions can be derived from the figure: a) the percentage of class A buildings reaching a maximum value of 30 that corresponds to small rural towns, b) class B and C buildings are predominant in Catalonia, their percentage reaching a value of 31 in the majority of municipalities; c) the highest percentage of class D buildings is only 14 and this is found in not many communities; d) the maps of figure 2 give an approximate indication of the different case of dwelling construction in the catalan municipalities. Finally, the percentage of buildings in each class obtained for Barcelona (the largest city in Catalonia) are 18% for class A, 61% for class B, 20% for class C, and 1% for class D; values that differ widely from the global percentages of the region.

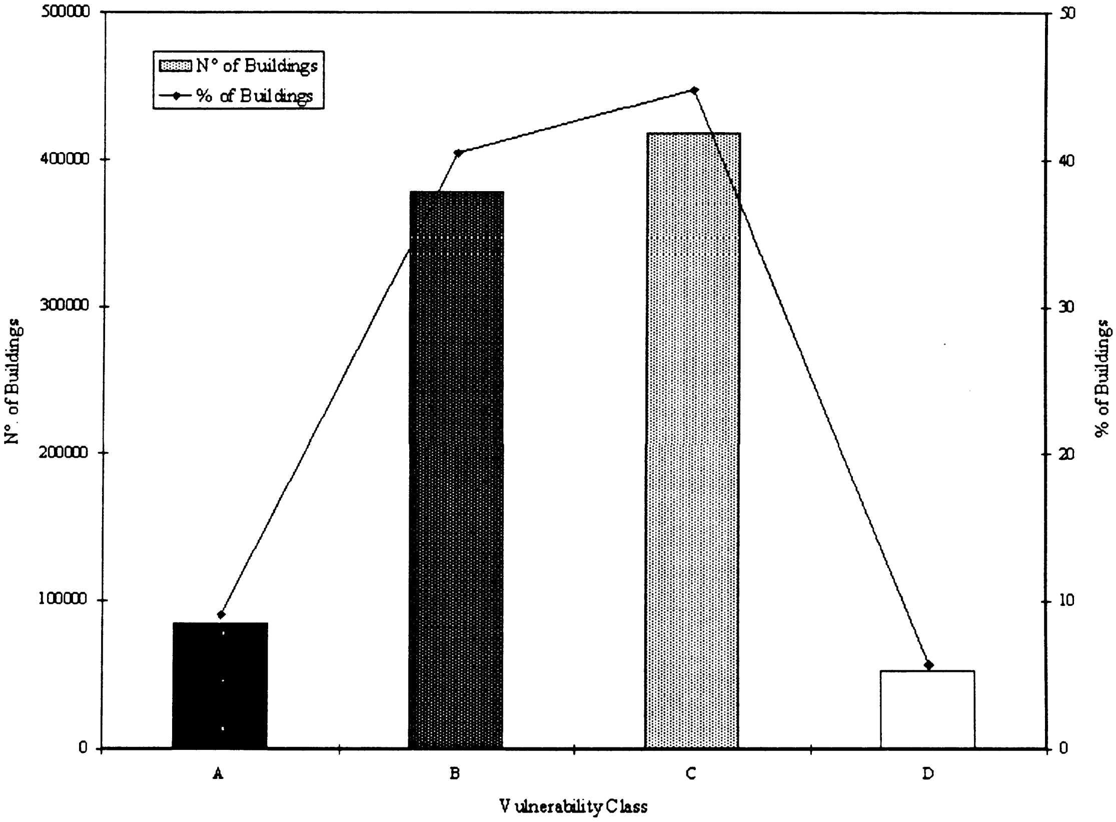

Figure 1. Classification of buildings in Catalonia in A, B, C and D vulnerability classes according to EMS-92.

3 PROBABLE DAMAGE TO BUILDINGS

3.1 *Damage Probability Matrices*

The damage that can sustain dwelling buildings in Catalonia from the action of earthquakes is estimated through the use of damage probability matrices (D.P.M.). We use D.P.M. obtained from the analysis of data on damage to buildings collected in Italy soon after the Irpinia earthquake of 1980. These data were classified in a scale of eight levels of damage (from no damage to collapse), that were correlated with those defined in the MSK-76 scale (Braga et al., 1982) as shown in table 3.

Table 3. Correlation and definition of damage in survey and MSK-76 scale.

MKS-76 Damage Level	Survey Damage Level	Description of Damage
0	1	No damage
1	2, 3	Slight: hair-line cracks, fall of small pieces of plaster.
2	4, 5	Moderate: cracks in many walls, fall of large pieces of plaster.
3	6	Heavy: large and extensive cracks in walls, fall of chimneys.
4	7	Destruction: gaps in walls, parts of buildings may collapse.
5	8	Total damage: total collapse of buildings.

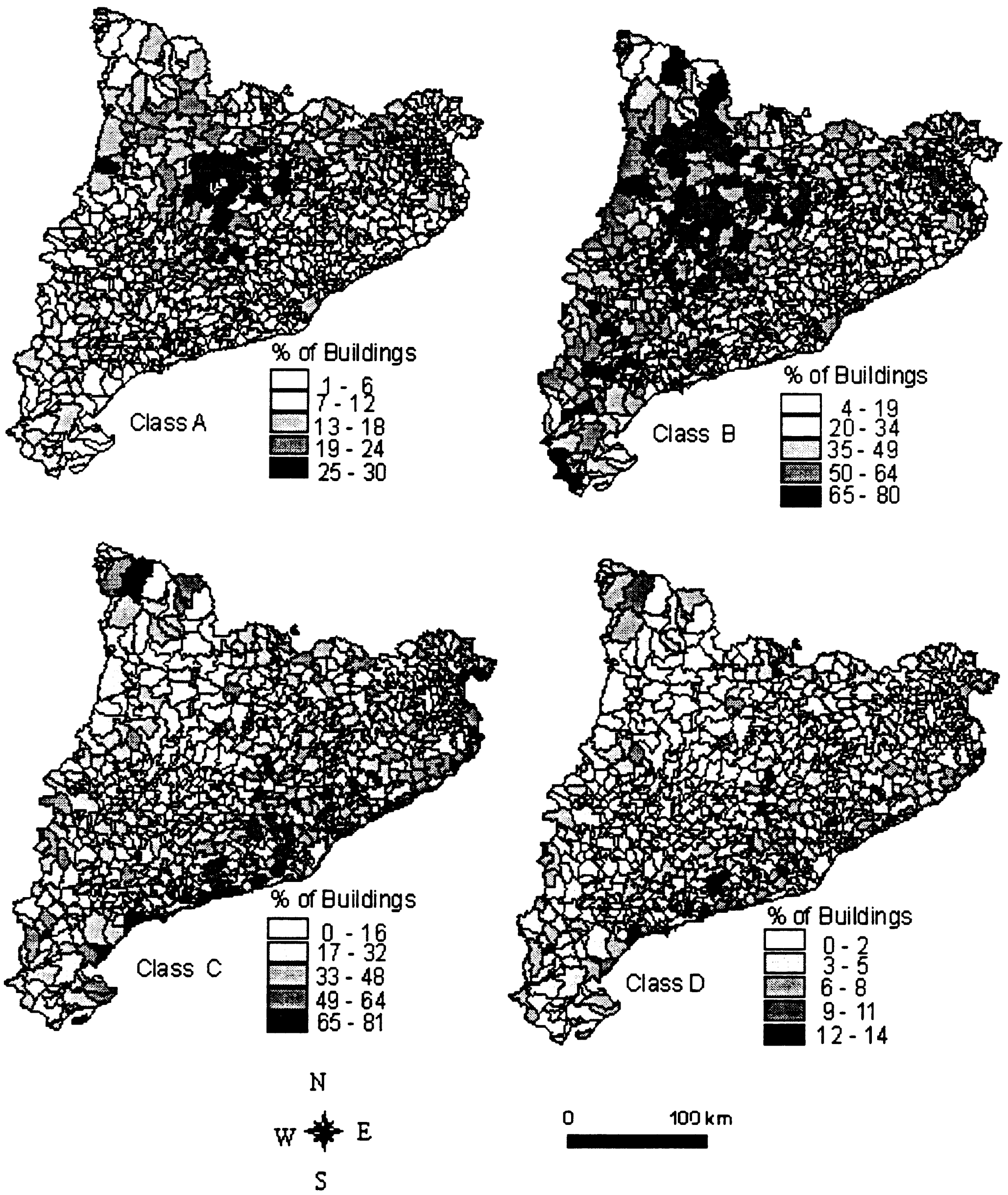

Figure 2. Distribution of vulnerability classes A, B, C, and D according to EMS-92 in all municipalities of Catalonia.

A total of 15 structural typologies were identified from the analysis of data of 32548 buildings in 41 Italian towns. Vertical and horizontal structure have been the essential elements in this process, since others parameters also available (such a type of roof, height, age, and number of common fronts with other buildings) had less influence on the building seismic vulnerability. The description of the fifteen structural typologies and the number of buildings in each one is given in table 4.

Table 4. Typologies derived from the surveyed buildings and number of buildings for each one.

Horizontal Structure	Vertical Structure							
	Fieldstone		Hewn stone		Brick masonry		Reinforced Concrete	
	Type	No. of buildings	Type	No. of buildings	Type	No. of buildings	Type	No. of buildings
Vaults	1	1540	5	618	9	17	-	-
Wooden	2	8996	6	3322	10	137	-	-
Steel	3	5375	7	2584	11	535	-	-
R.C. (1-3 floors)	4	945	8	3555	12	829	13	3186
R.C. (4-6 floors)	-	-	-	-	-	-	14	869
R.C. (> 6 floors)	-	-	-	-	-	-	15	40

These structural typologies have been grouped in the vulnerability classes given in the EMS-92 (Chávez et al., 1998) from consideration of the definitions included in the European Scale and the seismic behaviour of buildings , this behaviour has been analysed statistically; a mean damage level $\bar{x}_j$, associated to typology *j*, was computed form all damage data of buildings of such typology by the expression:

$$\overline{x}_j = \sum_{i=0}^{n} \frac{e_i \cdot x_i}{N} \tag{1}$$

where e_i = number of buildings, of typology *j* that suffered damage of level x_i; n = number of levels of damage; and N = total number of buildings. The mean level of damage for each typology and its standard deviation are shown in figure 3. The variation of this parameter with typology can be compared with the vulnerability assigned in next paragraph.

EMS-92 gives more importance to the vertical structural element in the definition of vulnerability classes, and, as may be seen, this criterion is also valid in almost all typologies identified from the Irpinia earthquake; however in the case of typology 2 (field stone with steel floor) the differences, for the same vertical structural element are very large (Figs 3-4).

The classification adopted of the fifteen typologies according to the vulnerability classes of the EMS-92 is represented in figure 4, where the distribution of damage in each typology is also shown. The first three typologies, in white colour (8, 12 & 13) are considered as of D vulnerability class; the following four, in grey colour, (10, 11, 14 & 15) are class C; the three in dark grey are class B and the last five, in black (1, 2, 5, 6, 9) are class A.

The seismic intensity reached by the ground motion in every municipality was then estimated. For each town the percentage of every level of damage shown in buildings of each vulnerability class was computed, and the corresponding intensity was assigned by comparison with the definitions of EMS-92; the intensities obtained range from VI to IX.

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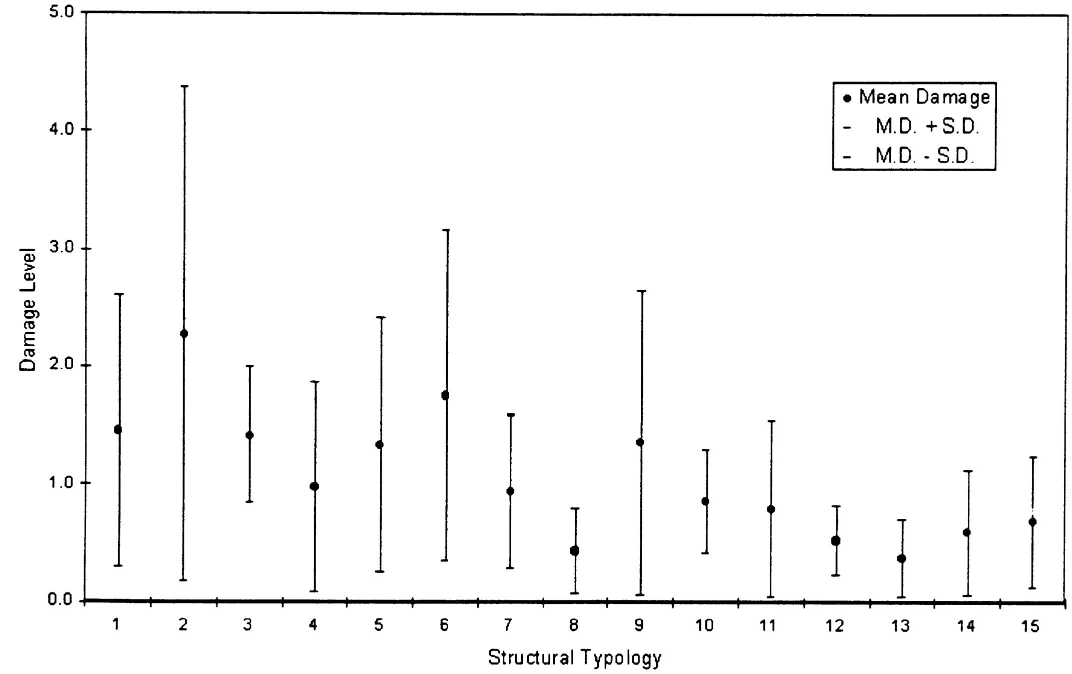

Figure 3. Mean damage level and standard deviation for each typology.

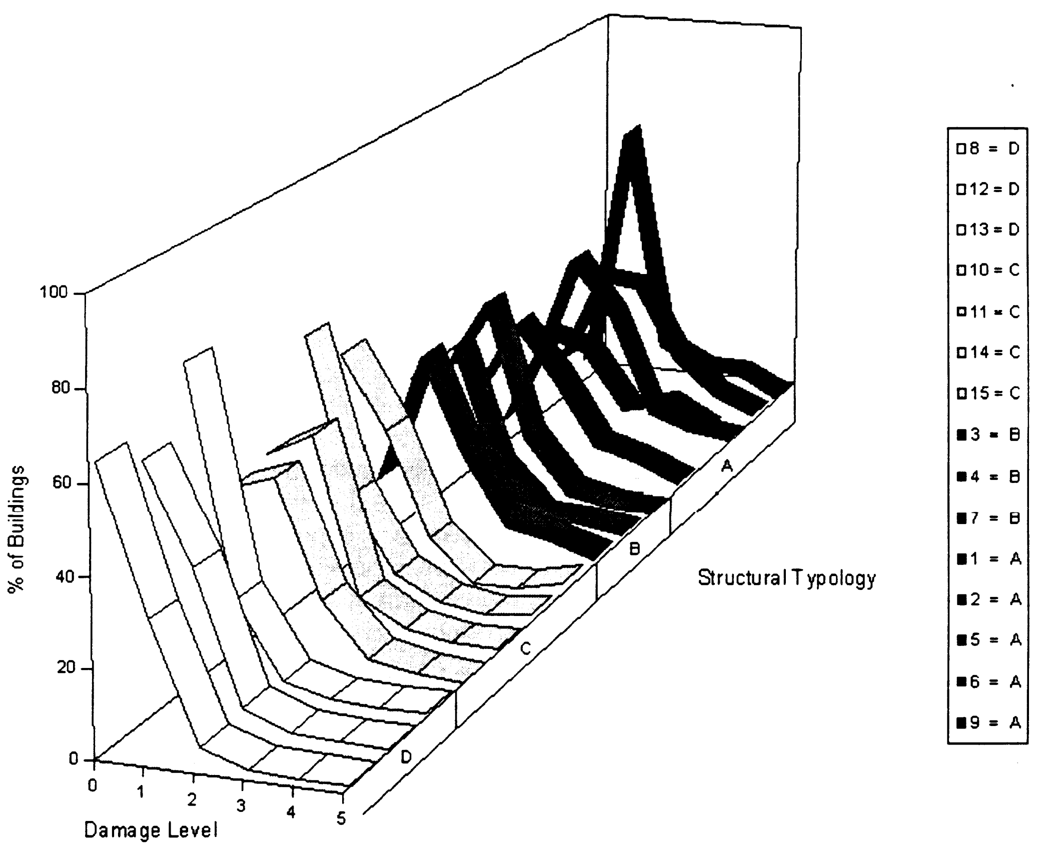

Figure 4. Distributions of damage observed in the fifteen structural typologies organized according to A, B, C and D vulnerability classes.

The last step in the process was to group, by level of damage, the vulnerability classes of building, belonging to towns that sustained the same ground intensity. The percentage distributions obtained in this way are considered as the damage probability matrices for the A, B, C and D vulnerability classes; they represent the conditional probability that buildings of a given vulnerability class suffer damage of a particular level in the case that a certain value of ground intensity is reached. These matrices have been fitted to several theoretical distributions, such as normal Poisson and binomial; the best fit is obtained for the binomial distribution. The matrices proposed for estimating the earthquake damage to buildings, are shown in figure 5, for intensities VI to IX.

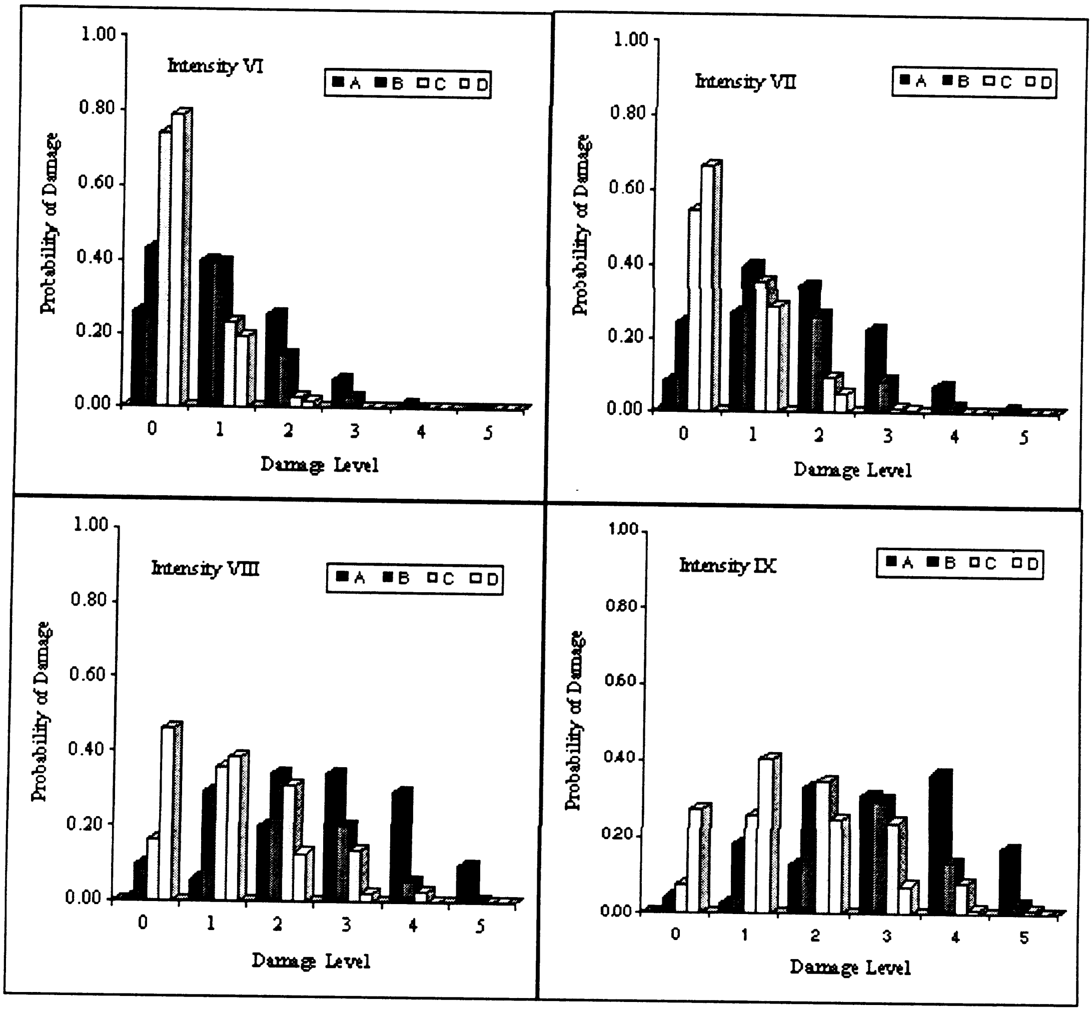

Figure 5. Damage probability matrices for A, B, C & D vulnerability classes according to EMS-92.

3.2 *Probable Damage from earthquake to buildings in Catalonia*

Earthquake damage to buildings in Catalonia can be evaluated in the scale given in table 3, used also in the definition of the damage probability matrices shown in the previous paragraph. The probability P[Dk] of having a damage of level k in a town may be estimated by means of the expression (2).

$$P[Dk] = \Sigma_I \Sigma_T P[Dk \mid I, T] * P[I] * P[T] \quad (2)$$

where P[T] is the probability that buildings in the town belong to vulnerability class T (which is given by their percentage distribution by classes); P[I] represents the seismic hazard (that is, the probability of each level of intensity to occur); and P[Dk|I,T] is the conditional probability that a damage level k takes place in buildings of vulnerability class k for seismic intensity I (as is given by the Damage Probability Matrices).

A simplification of expression (2) was used to estimate the damage distribution in a town as a result of a seismic intensity I.

$$P_I[Dk] = \sum T \; P[Dk \mid I, T\,] * P[T] \qquad (3)$$

The value of intensity we considered in the computation of $P_I[Dk]$, for each town, was that corresponding to a return period of 500 years as given by the Spanish Seismic Code NCSE-94, which, for Catalonia varies from VI to VIII. As an example, figure 6 shows the results of the computation for the city of Barcelona for two intensities, VI and VII.

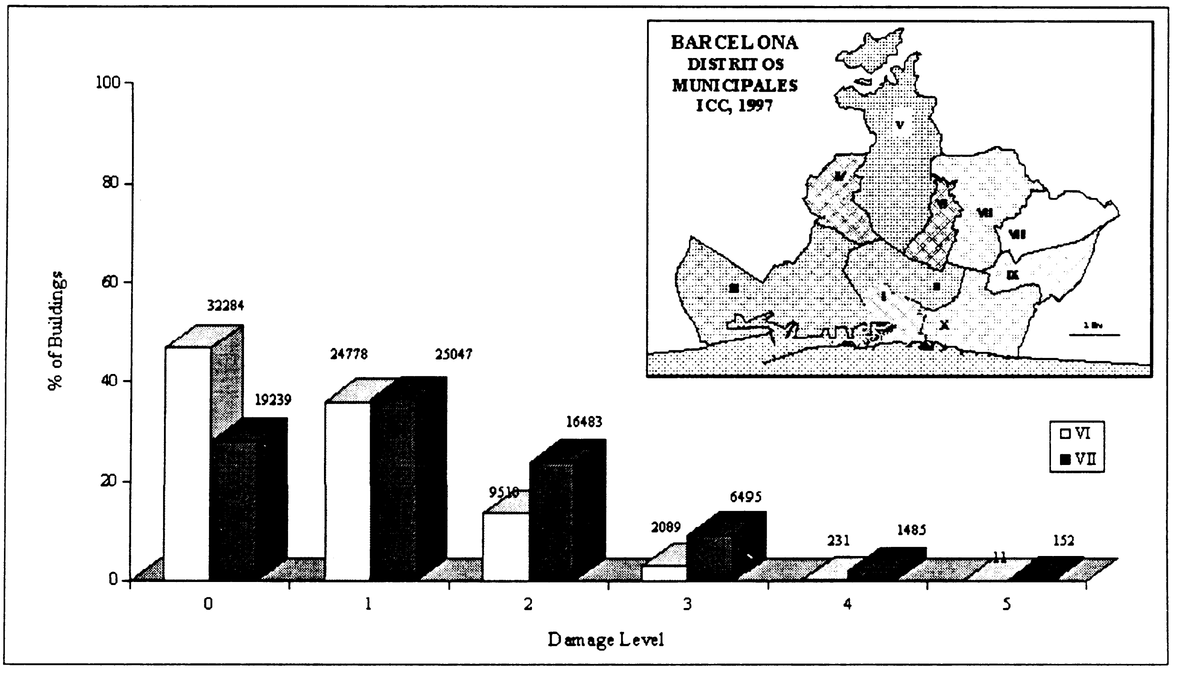

Figure 6. Distribution of Damage in the city of Barcelona for VI & VII seismic intensities.

4 ESTIMATION OF HUMAN CASUALTIES AND ECONOMIC LOSSES FROM EARTHQUAKE DAMAGE TO BUILDINGS. METHODOLOGY.

4.1 *Estimation of human casualties*

The estimation of human casualties in seismic events is one of the main objectives of seismic risk studies. In this work, the estimation is carried out by means of methodologies developed by Coburn et al (1992) for the case of collapse of buildings, and by the Applied Technology Council (ATC-13, 1985) for damage of various degrees.

The Coburn methodology developed from the study of more than a thousand destructive earthquakes distributed all over the world, which caused a total loss of live exceeding 1.5 million people. It applies only to loss of life caused by structural collapse of buildings, which is responsible for the 75% of deaths in earthquakes. The expression proposed by Coburn is:

$$Ks_b = D5_b * [M1_b * M2_b * M3_b * (M4_b + M5_b)] \quad (4)$$

where b indicates the type of buildings, D5 the number of collapsed buildings, M1 the average population per building, M2 the occupancy at the time of the earthquake, M3 the occupants trapped by building collapse, M4 mortality at collapse, and M5 mortality post-collapse.

The ATC-13 methodology proposes specific percentages of deaths and injuries for each level of building damage. These percentages were derived from the analysis of past earthquakes in the United States, carried out by a group of experts for the State of California. Casualties derived from both, structural and non structural building damage can be estimated by this procedure.

4.2 *Estimation of economic losses*

A preliminary estimation of economic losses from earthquakes in Catalonia was obtained using a correlation between level of damage and global damage index of buildings. The approximation can be applied to masonry buildings (the most abundant in Catalonia) and in regional studies (Yepez, pers comm.). The correlation between the two parameters used here is presented in table 5, developed in the United States (Yepez, 1996).

Table 5. Correlation between damage level and replacement cost

Damage level	Replacement cost (%)
1	1
2	20
3	40
4	80
5	100

The estimation made takes into account only the damages to building by ground shaking (direct damage); hazards that follow the earthquakes, such as fire, landslides, liquefaction, etc, are not considered, variation in economic value due to inflation are included. However, adverse economic effects following the earthquake are not taken into account. One such effect could be increase of replacement value due to increase in the price of row materials or due to increase in labor costs because of high demands, (Kiremidjian, 1992); this means that losses may be underestimated by the procedure we have followed.

5 DAMAGE SCENARIOS ESTIMATED FOR CATALONIA

Damage scenarios for all municipalities of Catalonia have been estimated considering, for each location, the macroseismic intensity given by the Spanish Seismic Code (that corresponding to a 500 years return period). The probable number of people killed, injuried, trapped by collapse buildings or made homeless has been obtained. The resources needed to minimize disruption, rescue people buried, accommodate homeless, and minimize the recovery period can be estimated from these data (Coburn & Spence, 1992).

As an example, two estimated damage scenarios (intensities VI and VII) for the city of Barcelona are shown in table 6. In the table, buildings with serious damage that prevent their use, are considered those with damage of levels 5 and 4, and 50% of those that suffered damage of level 3. The mean population per building was considered in estimating the number of homeless. Economic losses are given in millions of Euros.

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Table 6. Damage scenarios for the city of Barcelona.

Damage	Intensity	
	VI	VII
Buildings with serious damage	1288	4885
Collapsed buildings	12	152
Homeless	28336	107470
Injuries	4361 - 4252	19904 - 18569
Killed	161 - 265	1006 - 2340
Economical losses (Euros)	1181	3393

6 SUMMARY AND CONCLUSIONS

A methodology for estimating vulnerability and seismic risk at a regional level has been presented. it includes four steps: classification of buildings in the region into the vulnerability classes of the EMS-92; estimation of damage probability matrices, derived from Italian data; assessment of human casualties due to damage to buildings, by means of ATC-13 and Coburn et al. Methodologies; and evaluation of economic losses.

The information used in the classification of catalan buildings into vulnerability classes include: data from the 1990 census on height, age, and location of buildings, the historical evolution of construction practices in Catalonia; the state of preservation of buildings, derived from a study carried out on a representative sample of catalan buildings, and the opinion of experts on the different subjects considered in this work.

Most of this information is available for other regions. Thus, the simple methodology described can be used to obtain a first approximation of their seismic risk.

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