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A METHOD TO PERFORM COMPUTER SIMULATIONS OF DAMAGE IN BUILDINGS FOR SEISMIC RISK EVALUATIONS

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ABSTRACT

A method to obtain damage probability matrices and vulnerability functions for building structures is presented. The behaviour of typic non-reinforced masonry and reinforced concrete buildings (moment resisting frames and flat slab buildings) existing in a specific region, is simulated for different levels of expected seismic action in that region. The structural seismic quality of buildings is evaluated using the italian vulnerability index, useful for large scale studies. From a probabilistic analysis and from a calibration procedure of the results, using the actual damage information of the region, damage matrices and vulnerability functions are obtained and applied to the study of an area of Barcelona, Spain. Finally, damage scenarios for that area are developed.

KEYWORDS

Seismic vulnerability, damage matrix, damage simulation, vulnerability function, damage scenario, non-reinforced masonry, reinforced concrete, nonlinear analysis, non-seismic details, damage index, vulnerability index.

INTRODUCTION

One main problem in seismic risk evaluation is the lack of information about damage in structures due to past earthquakes, specially in low or moderate seismic hazard zones. The use of available information for different regions than the studied one is not valid, due to the different characteristics of structures, soil, seismic source, etc. An alternative to obtain this information is to apply simulation procedures of the structural behaviour of buildings with the same characteristics as the ones to be studied, using reliable nonlinear dynamic models able to provide the damage in structural elements due to different expected earthquake levels.

The result of vulnerability studies is the expected grade of damage that would suffer a specific typology of structure due to a characteristic seismic action. It can be obtained by means of: 1) *damage probability matrices*, where the conditional probability $P[D = j|i]$ of occurrence of a j damage level due to an earthquake of i size is expressed in a discret form; and 2) *vulnerability functions* that show, in a continuous manner, the vulnerability as a function of some parameter describing the earthquake size. Therefore, the specific risk S can be evaluated by means of (Yépez *et al.*, 1995a):

1. Damage probability matrices

$$S = \sum_j \sum_i P[D = j|i] \; P[i] \tag{1}$$

where S is the conditional probability of occurrence of a j damage level, due to an earthquake of i intensity, multiplied by the occurrence probability of the earthquake with a specific return period.

2. Vulnerability functions

$$F(\bar{d}) = \int_0^{\bar{d}} \int_0^{I_{\max}} f(d|I) \; f(I) \; \mathrm{d}I \; \mathrm{d}d \tag{2}$$

$$S = F(d_{\max}) \tag{3}$$

where $F(\bar{d})$ is the damage cumulative distribution function for $d = \bar{d}$, whenever these variables can be considered random, independent and continuos in their definition range. $f(d|I)$ is the damage conditional density function over the I intensity, and $f(I)$ is the intensity density function. The seismic risk S is evaluated by equation (3), using the maximum values of the variables.

The aims of this paper are: to perform a seismic damage simulation in existing buildings of a specific region; to propose a calibration procedure of the syntethic vulnerability functions using the available damage information in structures and to deduce damage probability matrices applicables to the considered region. As an example, the simulation is performed for non-reinforced masonry and reinforced concrete buildings existing in Spain.

QUALIFICATION METHOD AND AVAILABLE DAMAGE INFORMATION

As mentioned before, the vulnerability index method has been chosen for the structural seismic evaluations. The most important parameters controlling the damage in buildings are clearly identified and qualified individually, in a weighted numerical scale, to emphasize their relative importance (table 1). Using observed values, a global building qualification is performed, through a vulnerability index I_{v}. For non-reinforced masonry structures, the index can be evaluated by (CNR, 1993)

$$I_{\mathrm{v}} = \sum_{i=1}^{11} K_i \; * \; W_i \tag{4}$$

This index has been normalized in this paper. For reinforced concrete structures, I_{v} can be evaluate by means of (CNR, 1993):

$$I_{\mathrm{c}} = \sum_{i=1}^{11} K_i$$

$$I_{\mathrm{v}} = -10.07 * (I_{\mathrm{c}} - 0.25) \quad \text{if} \quad I_{\mathrm{c}} \geq -6.5 \tag{5}$$

$$I_{\mathrm{v}} = 67.972 - 1.731 * (I_{\mathrm{c}} + 6.5) \quad \text{if} \quad I_{\mathrm{c}} < -6.5$$

The damage index D can be defined as a combination of values assigned to the different structural and non-structural components, given as a percentage. It can be related to the vulnerability index using the so-called vulnerability functions. On the other hand, a post-earthquake study has been performed after the 23/Dec/93 and the 4/Jan/94 crustal earthquakes occurred in south Spain ($I_{\max}$ =VII MSK). Many masonry and concrete structures were seriously damaged. The vulnerability and damage indexes were determined for each studied masonry building and the vulnerability function for VII MSK intensity was obtained by means of a statistical analysis (Fig. 1) (Yépez *et al.*, 1995a).

Table 1. Numerical scale for the computation of the vulnerability index I_V.

	Structural typology →	masonry					concrete		
i	Qualification Parameter	$K_i = A$	$K_i = B$	$K_i = C$	$K_i = D$	W_i	$K_i = A$	$K_i = B$	$K_i = C$
1	Resistance system organization	0	5	20	45	1.0	0.00	−1.00	−2.00
2	Resistance system quality	0	5	25	45	0.25	0.00	−0.25	−0.50
3	Convencional resistance	0	5	25	45	1.5	0.25	0.00	−0.25
4	Position of building and foundation	0	5	25	45	0.75	0.00	−0.25	−0.50
5	Horizontal floor system	0	5	15	45	1.0	0.00	−0.25	−0.50
6	Plant configuration	0	5	25	45	0.5	0.00	−0.25	−0.50
7	Elevation configuration	0	5	25	45	1.0	0.00	−0.50	−1.50
8	Maximum distance between walls	0	5	25	45	0.25	0.00	−0.25	−0.50
9	Roof type	0	15	25	45	1.0	0.00	−0.25	−0.50
10	Non structural elements	0	0	25	45	0.25	0.00	−0.25	−0.50
11	Preservation state	0	5	25	45	1.0	0.00	−0.50	−1.00

STRUCTURAL MODELS AND SEISMIC ANALYSIS

Non – reinforced masonry buildings

It is necessary to determine a model capable to represent the inelastic behaviour of non-reinforced masonry and their failure modes due to flexion-compression and shear stresses, including instability effects and lateral buckling. The Abrams's model (Abrams, 1992) has been chosen and applied to structures modelled as shear building or shear panel, depending on the floor flexibility. The maximum wall capacity to resist lateral loads has been evaluated and a damage index has been computed using the relation between the maximum panel shear stress produced by the seismic action and a function depending on the shear stresses corresponding to the initial and maximum panel cracking before the collapse (Yépez *et al.*, 1995a). After weighting floor damage indexes, a global damage index is obtained. Probable local soft story failures, considered as collapse state, can be also detected.

Reinforced concrete buildings

Analysing the concrete buildings studied in this work, two different structural systems have been identified: moment resisting frames and flat-slab structures. Although these structures have been designed using equivalent seismic forces in accordance to the spanish code (CPNS, 1974), ductility requirements cannot be found in the drawing details, specially in the connections. Therefore, a model describing the nonlinear performance of non-ductile structures must be applied.

For non-linear time history analysis, the IDARC program (Kunnath *et al.*, 1992) has been used. However, additional computer modules to improve the model of the studied buildings have been added. For moment resisting frames, the modules are able to compute, to revise and to modify the moment-curvature hysteretic relations of beam and column cross sections. Following the procedure proposed by Hoffman *et al.*, (1992), the cross section behaviour can be modelled, considering non-ductil details of beam-column joints, such as: discontinuous positive flexural reinforcement, lack of joint shear reinforcement and inadequate transverse reinforcement for core confinement. For flat-slab structures, additional modules compute, revise and modify the mentioned hysteretic relations for columns and equivalent beams, modelling the non-ductile details of slab-column connections. The Durrani*et al.*, (1992) procedure was used. These type of details are expected to limit severely the moment transfer capacity and shear resistance of connections, lacking the ability to prevent progressive collapse of floors after punching failures.

A local structural damage index of each element is computed, using the modified Park, Ang & Wen index (Kunnath, *et al.*, 1992). It represents a combination of the deformation damage and the damage due to dissipated hysteretic energy. In addition, revisions of all structural element cross sections during the dynamic analysis can detect local soft story failures, considered as a collapse state. This process requires the detection of plastic hinges in all structural elements.

Levels of seismic action

Syntethic accelerograms have been generated from spanish seismic code response spectra in rock (NCSE, 1994), for different values of peak ground acceleration related with probable intensities in the studied zone. The convolution of the subsoil transfer functions of the zone with the accelerograms yields the final seismic input for structural models.

Economic damage index

For masonry buildings, the global structural damage index has been considered equal to the economic damage index, defined as repair costs over replacement costs. For concrete buildings the method proposed by Gunturi (1993) has been used, taking advantage of existing relations between the Park index and the economic damage index of the structural components. Existing relations between story drift or maximum floor acceleration and the economic damage index of non-structural elements have been also applied. After a weighting, based on global costs of building components, a global economic damage index is obtained. From now on, any reference to a damage index will correspond to the global economic damage index.

SIMULATION AND CALIBRATION OF VULNERABILITY FUNCTIONS

In Spain the available damage information corresponds to masonry buildings (VII MSK); therefore, the calibration is only possible for these structures. The procedure starts obtaining the VII MSK simulation and a regression analysis. The result needs to be calibrated with the observed curve (Fig. 1). One possible way is to modify W_i weights, holding their proportional relations, because the vulnerability index method parameters are hierarchical using these relations. The suggested calibration is performed by searching roots of regression equation followed by a conditional generalized inversion of equation (4) and performing new regressions. After an iterative process, the simulated and the calibrated functions and the new W_i values (table 2) were obtained for the studied region (Fig. 2) (Yépez *et al.*, 1995b). Atferwards, for near 2000 synthetically generated buildings, the numerical procedure explained before was applied and the final simulation function was obtained (Fig. 3).

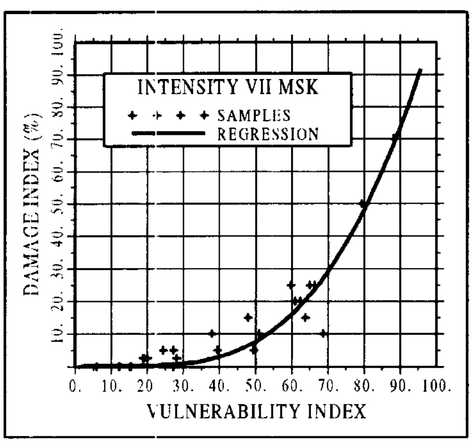

Fig. 1. Observed vulnerability function for masonry buildings, $I_{\rm MSK}$ = VII.

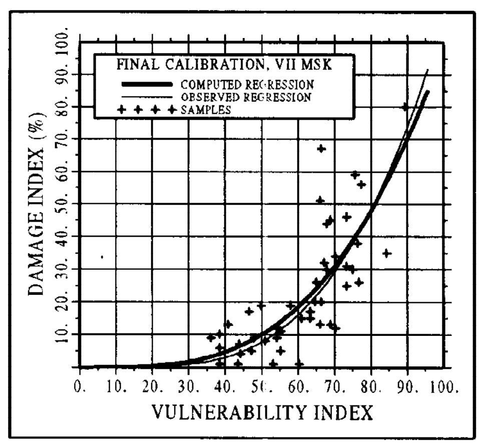

Fig. 2. Building simulation, $I_{\rm MSK}$ = VII, and comparison with the observed function.

PROBABILISTIC STUDY AND FINAL RESULTS OF SIMULATION

The probabilistic equation for the specific seismic risk using the vulnerability index method is:

$$F(\bar{d}) = \int_0^{\bar{d}} \int_0^{I_{\rm v max}} \int_0^{I_{\rm max}} f(d \mid I_{\rm v}, I)\; f(I_{\rm v})\; f(I)\; {\rm d}I\; {\rm d}I_{\rm v}\; {\rm d}d \qquad (6)$$

where $F(\bar{d})$ is the damage cumulative distribution for $d = \bar{d}$. $f(d|I_{\rm v}, I)$ is the damage conditional density function over $I_{\rm v}$ and I intensity; $f(I_{\rm v})$ and $f(I)$ are the density functions of $I_{\rm v}$ and I.

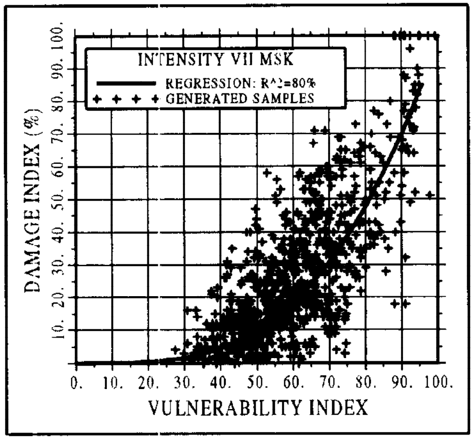

Fig. 3. Final building simulation and polynomial regression, I_{MSK} = VII.

Weight W_i	Original	Iter 1	Iter n
1	1.00	1.015	1.095
2	0.25	0.254	0.274
3	1.50	1.523	1.643
4	0.75	0.762	0.821
5	1.00	1.015	1.095
6	0.50	0.508	0.548
7	1.00	1.015	1.095
8	0.25	0.254	0.274
9	1.00	1.015	1.095
10	0.25	0.254	0.274
11	1.00	1.015	1.095

Table 2. W_i proposed by italian method and obtained from the iterative process.

For masonry buildings, the simulation is now applied to other intensities and for the same buildings generated before, but using the new W_i values. For concrete buildings, the procedure is applied for all intensities and for more than 100 hypotethical buildings, but without calibration. For each intensity level, 10 syntethical ground motions have been generated and applied to each simulated structure. The Montecarlo simulation has been used for the generation of material properties, reinforcement and geometrical characteristics of structures and to obtain the necessary parameters for the syntethical generation of ground motions. The Updated Latin Hypercube Sampling technique has been applied to optimize the procedure (Florian, 1992). $f(I_{\mathrm{v}})$ and $f(d \mid I_{\mathrm{v}}, I)$ have been defined by probability laws, fitting the results with 5%-10% of significance level, as seen in figures 4 and 5. $f(I)$ is determined from hazard studies. The conditional probability $P[d \mid \Delta I_{\mathrm{v}}, \Delta I]$ can be obtained discretizing (6) in a damage probability matrix form

$$P[d_i < d < d_{i+1}] = \sum_{k=1}^{n} \sum_{j=1}^{m} P[d_i < d < d_{i+1} | I_{\mathrm{v}_j} < I_{\mathrm{v}} < I_{\mathrm{v}_{j+1}}, I_k < I < I_{k+1}] \times P[I_{\mathrm{v}_j} < I_{\mathrm{v}} < I_{\mathrm{v}_{j+1}}] \times P[I_k < I < I_{k+1}] \qquad (7)$$

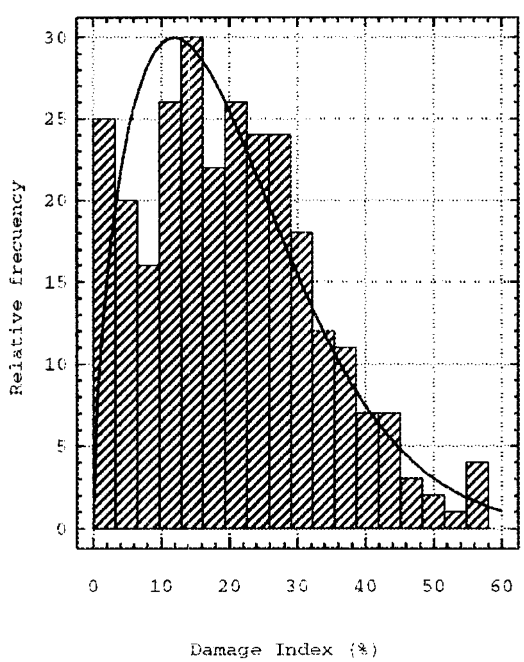

Fig. 4. Lognormal damage distribution. $I_{\mathrm{v}} \in$ [45,60], I_{MSK} = VII, for non-reinforced masonry buildings.

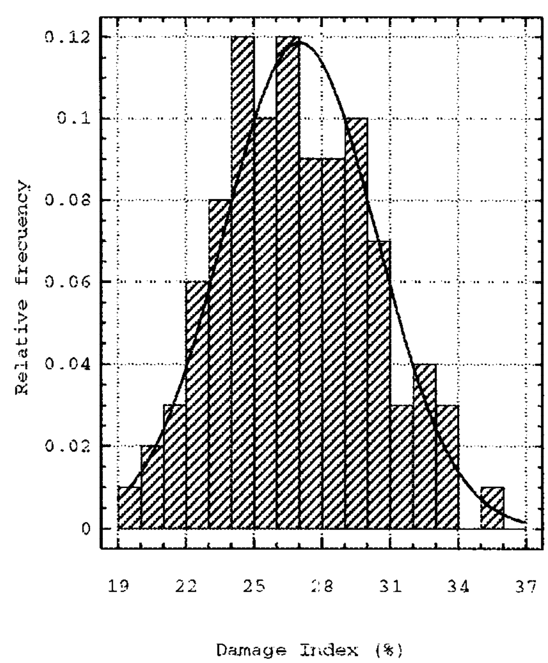

Fig. 5. Normal damage distribution . $I_{\mathrm{v}} \in$ [35-45], I_{MSK} = VIII, for concrete flat-slab buildings.

where $P[d_i < d < d_{i+1}]$ is the damage probability within the (d_i, d_{i+1}) interval. The first factor at the right hand side member is the damage conditional probability over I_V and I. The other two factors represent the total probability for I_V and I; m and n are the numbers of ΔI_V and ΔI, respectively. As a final result, vulnerability functions for different intensities (Figs. 6, 7, 8) were obtained and, from the discretization, damage matrices were developed (as the ones in tables 3 and 4).

Table 3. Discretized values of $f(d \mid I_V, I)$, from models fitted to the simulated data I_{MSK} = VII, for non-reinforced masonry buildings.

$f(d \mid I_V, I)$	0 – 20	20 – 40	40 – 60	60 – 80	80 – 100
0 – 30	0.980	0.020	0.000	0.000	0.000
30 – 45	0.881	0.113	0.006	0.000	0.000
45 – 60	0.561	0.353	0.076	0.009	0.001
60 – 75	0.186	0.448	0.309	0.055	0.002
75 – 90	0.052	0.168	0.312	0.293	0.138
90 – 100	0.001	0.010	0.073	0.237	0.352

Table 4. Discretized values of $f(d \mid I_V, I)$, from models fitted to the simulated data I_{MSK} = VII for flate-slab buildings.

$f(d \mid I_V, I)$	0 – 20	20 – 40	40 – 60	60 – 80	80 – 100
0 – 25	0.636	0.364	0.000	0.000	0.000
25 – 35	0.319	0.593	0.080	0.007	0.000
35 – 45	0.052	0.905	0.043	0.000	0.000
45 – 55	0.003	0.405	0.580	0.012	0.000
55 – 100	0.000	0.159	0.782	0.059	0.000

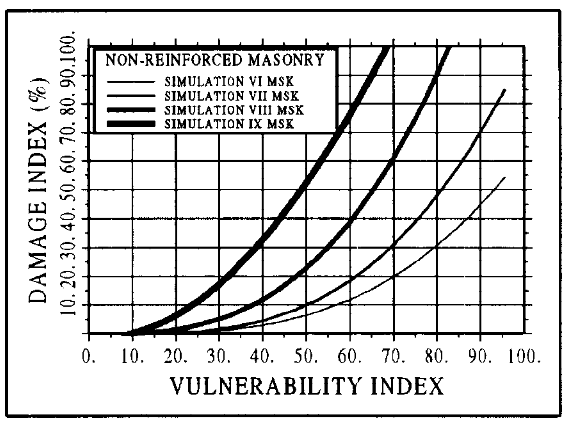

Fig. 6. Vulnerability functions obtained by simulation, for masonry buildings.

APPLICATION OF THE RESULTS TO BARCELONA, SPAIN

One central zone of Barcelona called the "Eixample" has been chosen. From available structural drawings found in the historic city archives, it has been posible to obtain the required structural characteristics. From the inspection of the selected buildings, a complete description of the parameters has been obtained. Finally, the vulnerability index has been calculated and, making use of the vulnerability functions obtained before, the damage index was estimated with respect to the considered intensity level. The studied buildings have been organized in a random manner, forming blocks similar to the real ones. The entire computed process has been carried out using a Geographical Information System (GIS).

Figure 9 shows the arrangement of buildings in the simulated blocks and the I_V index –medium to high values– obtained. Although the studied buildings have a relative regularity in plant and elevation, the high values are due to the low quality of the materials, to the medium to low preservation state and

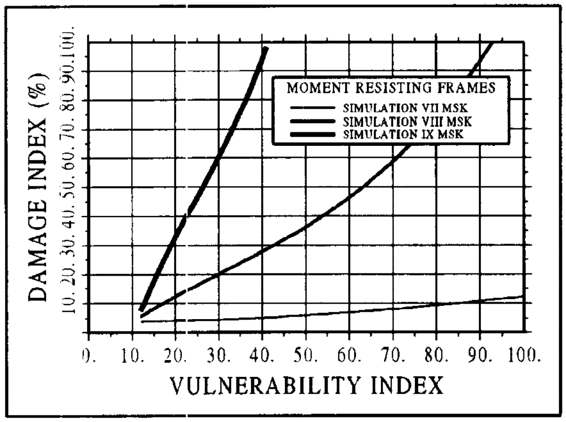

Fig. 7. Vulnerability functions obtained by simulation, for moment resisting frames.

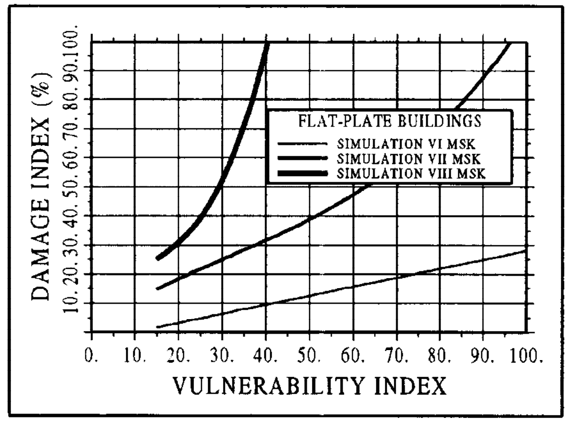

Fig. 8. Vulnerability functions obtained by simulation, for flat-slab buildings.

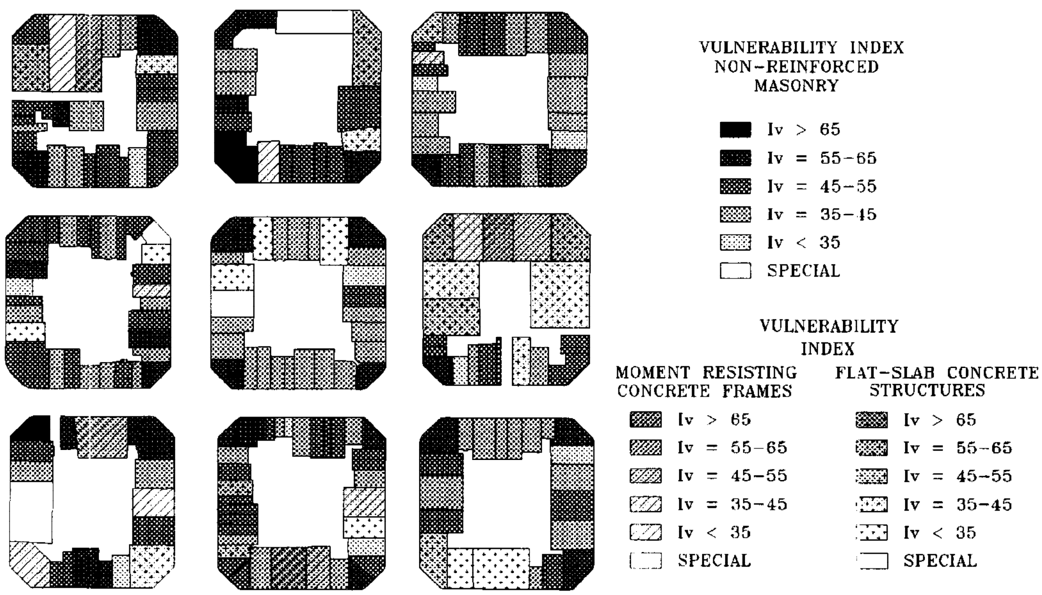

Fig. 9. Vulnerability map of the studied area.

to the fact that no seismic design details have been applied. The buildings without any identification correspond to special typologies. Figure 10 is the scenario for VIII intensity, showing very important damages. The major part ranges between 20% and 60% and, in some cases, over 60%. Collapse of some structures is possible. The flat-slab buildings are more dangerous than the moment resisting frames and the masonry structures. If earthquakes yielding an intensity similar to the simulated one would happen in the area, the degree of losses would be really high.

CONCLUSIONS

The developed methodology is appropiate to analize the global seismic behaviour of urban areas. It supplies enough information about the seismic performance of individual buildings, in order to take decisions and to reduce the dissaster effects. Vulnerability functions are simulated using a post-earthquake survey study and, based on a probabilistic study, damage matrices are obtained for the first time in Spain. The damage scenarios of the "Eixample" show middle and high building vulnerability indexes, in agreement with the actual state and the design details of the analyzed buildings. The scenarios show a bad seismic performance of concrete buildings. These structures presents a very high risk, specially the flat-slab buildings. The computer simulation has partially replaced the information that should be obtained from post-earthquake studies; however, it is essential to emphasize that damage surveys are always necessaries to calibrate the analytical results.

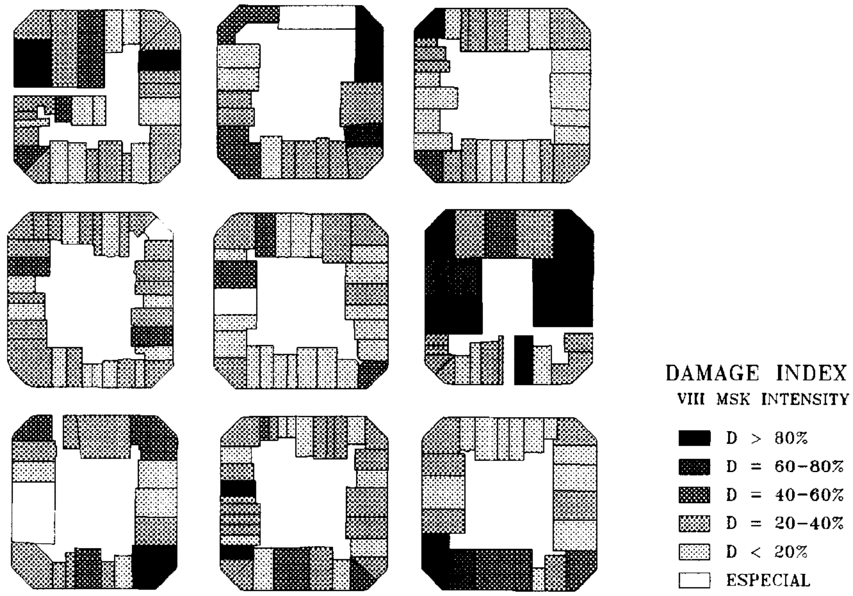

Fig. 10. Damage scenario for an earthquake of VIII MSK intensity level.

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