SEISMIC VULNERABILITY ASSESSMENT. METHODOLOGICAL ELEMENTS AND APPLICATIONS TO THE CASE OF ROMANIA*

Horea SANDI[1], Antonios POMONIS[2], Symon FRANCIS[3], Emil Sever GEORGESCU[4], Rakesh MOHINDRA[3], Ioan Sorin BORCIA[4]

ABSTRACT

This paper is intended to present some studies undertaken in order to develop a seismic vulnerability estimation system to fit the needs of development of earthquake scenarios and of development of an integrated disaster risk management system for Romania. Methodological aspects are dealt with, in connection with the criteria of categorization of buildings, with the definition of parameters used for characterizing vulnerability, with the setting up of an inventory of buildings and with the calibration of parameters characterizing vulnerability. Action was initiated along the coordinates referred to in connection with the methodological aspects mentioned above. The approach was made, as far as possible, specific to the conditions of Romania. Some data on results obtained to date are presented.

Keywords: seismic vulnerability, vulnerability estimation, earthquake scenarios, categorization of buildings, inventory of buildings, expected earthquake impact.

REZUMAT

Lucrarea are scopul de a prezenta o serie de studii întreprinse în vederea dezvoltării unui sistem de estimare a vulnerabilității seismice care să corespundă necesităților de dezvoltare a unor scenarii de cutremur şi de dezvoltare a unui sistem integrat de management al riscului seismic. Sunt abordate aspecte metodologice, în corelare cu criterii de clasificare a clădirilor, cu definirea parametrilor utilizați pentru caracterizarea vulnerabilității, cu dezvoltarea unui sistem de inventariere a clădirilor şi cu calibrarea parametrilor care caracterizează vulnerabilitatea. A fost inițiată activitatea orientată conform coordonatelor menționate, în corelare cu aspectele metodologice menționate mai înainte. Abordarea adoptată a fost adaptată, pe cât posibil, condițiilor din România. Sunt prezentate unele date privind rezultatele obținute până la elaborarea lucrării.

Cuvinte cheie: vulnerabilitate seismică, estimarea vulnerabilității, scenarii de cutremur, clasificarea clădirilor, inventarierea clădirilor, impact seismic aşteptat.

1. Introduction

Seismic hazard and risk are widely recognized as being high in Romania. Moreover, according to forecasts like those of (Constantinescu & Enescu, 1985) or (Sandi & Mârza, 1996), there is a high probability of occurrence of a new strong, perhaps destructive, earthquake, within the near future. This makes the need of developing and implementing efficient risk reduction strategies a matter of high urgency.

The basic ingredients required for the assessment of seismic risk are represented by the seismic hazard and by the seismic vulnerability of elements at risk dealt with (the exposure of elements at risk is to be added to them in case one considers elements at risk with variable exposure, like e.g. people at risk in an assembly hall). The experience acquired to date leads to the conclusion that the difficulties and uncertainties related to the seismic vulnerability appear to be, strangely, more important or severe, than those related to seismic hazard. This fact

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[1]M., Academy of Technical Sciences of Romania. E-mail: sandi@geodin.ro
[2]Risk Management Solutions, Athens, Greece. E-mail: antoniospom@forthnet.athens.gr
[3]RMSI Pvt Ltd, Noida, India. E-mail: rakesh.mohindra@rmsi.com
[4]INCERC (National Building Research Institute), Bucharest, E-mail: ssever@incerc2004.ro, isborcia@incerc2004.ro

obviously raises a challenge, related to the object of this paper.

In order to cope with the challenge of major social importance raised by seismic risk, the Romanian governmental agencies benefitted from the financial and technical assistance provided by the World Bank Office in Bucharest. Among a group of projects developed in this framework, the authors got involved in two projects, referred to as: AC3, "*Consultancy services for development of a Vrancea earthquake scenario*" and AC6, "*Consultancy services for integrated disaster risk management study*". The task of assessing seismic vulnerability of various categories of elements at risk was of obvious importance in both cases. At the same time, trying to assess seismic vulnerability raised several complicated problems of methodological and logistic nature. The paper presents some main aspects related to a first attempt of development of a nation-wide seismic vulnerability estimation system, concerning basically the existing building stock.

2. Methodological aspects concerning seismic vulnerability and deriving of basic data

2.1. General

There are several situations / reasons requiring the use of the concept of (seismic) vulnerability: Mainly, they are:

- use of vulnerability as one of the main factors involved in risk analysis;
- use of vulnerability as one of the main factors involved in development of scenarios;
- background for setting risk reduction strategies for the building stock or for other categories of elements at risk;
- providing a background for the development of seismic intensity scales (e.g.: the EMS-98 scale (Grünthal, 1998) refers explicitly and repeatedly to seismic vulnerability).

The concern that is specific to this paper is dealing with the seismic vulnerability of the building stock, in view of providing a suitable background for the development of seismic risk scenarios under the conditions that are specific to Romania.

The main problems of methodological nature dealt with in this frame concern:

- an appropriate definition of seismic vulnerability;
- development of appropriate ways for estimating vulnerability for selected categories of elements at risk;
- ways of setting up of corresponding databases;
- development of appropriate ways of use of results obtained.

2.2. Vulnerability related definitions

A qualitative definition of seismic vulnerability, that can be widely accepted, is as follows: *the proneness of some category of elements at risk to undergo adverse effects inflicted by potential earthquakes*. This kind of definition, which is definitely vague, requires of course considerable refinements in order to become an operational tool for various purposes, like estimate of seismic risk, development of earthquake scenarios, or development of strategies of risk mitigation. The refinements required refer essentially to:

- the specification and characterization of elements at risk for which seismic vulnerability is to be investigated;
- the characterization of seismic action and the quantification of its severity;
- the characterization of potential earthquake effects and the quantification of their severity;
- the characterization of the proneness to occurrence of effects of various levels of severity, as a function of the severity of seismic action.

The concept of vulnerabillity pertains to a system of basic concepts involved in risk analysis. These are considered in this paper only in relation to seismic risk. A basic list of them is: *elements at risk*, *action* (*seismic*), *hazard* (*seismic*), *potential effects* (*damage*, *losses*),

exposure, vulnerability and *risk*. Besides this basic list one can consider also the concept of *earthquake scenario*, which represents a simpified substitute for risk, used in practice due to the lack of feasibility of proper risk analyses. Potential effects, exposure and vulnerability represent characteristics of the categories of elements at risk dealt with and are specific to them. E.g.: potential effects may be damage to buildings or other artifacts of man, casualties or injuries to people; exposure may be permanent and constant for buildings, but variable for people at risk in an assembly hall. The earthquake effects are highly random, so randomness must be explicitly recognized in dealing with vulnerability. In this frame, vulnerability is characterized in probabilistic terms, by means of distributions of expected effects, conditional upon some parameter(s) characterizing the severity of (seismic) action.

The situations in which vulnerabilty is to be dealt with are extremely diverse. To consider some examples:

- the action can be considered in terms of scalar or of vectorial characteristics;
- the action can be considered at source level, at site level, at floor level etc.;
- the elements at risk dealt with may be located at a definite (single) place or they can be represented by geographically distributed systems (e.g.: lifelines);
- the potential effects may be damage to artifacts of man, adverse effects to people, financial losses, functional impairement etc.;
- vulnerabilility may be dealt with in relation to elements at risk (e.g. buildings) in their initial state, or in relation to the consideration of cumulative effects of repeated cases of incidence of action (evolutionary vulnerability);
- the concern for vulnerabililty analysis may be related to a definite object (or system), or it can be related to the develop-ment of databases for some categories of systems.

The examples referred to illustrate the diversity of needs of specific approaches in various possible applications. Some attempts at dealing (at least partially) with such a manifold of situations were presented in (Sandi, 1985), (Sandi, 1986), (Sandi, 1998), (Sandi, 2003).

As a reply to the questions that may be raised by the manifold of possibilities referred to previously, the framework adopted in this paper may be characterized as follows:

- the action is considered in scalar terms only;
- the action is considered at site level;
- the elements at risk are as a rule buildings, located, each of them, at some definite place (some references to another category of elements at risk, represented by their occupants, are made too);
- the potential effects are represented basically by damage to buildings (when dealing with their occupants, one will consider, of course, casualties or injury cases of various levels of severity);
- no specific developments concerning evolutionary vulnerability are presented;
- attention is paid mainly not to individual buildings, but to the various categories of buildings of which the building stock consists.

In order to make following discussion more specific, the *elements at risk* considered at this place, which are some categories of artifacts of man, more precisely some categories of (individual) buildings, are to be specified further on in some general terms, like:

- period of construction;
- material of construction and structural system;
- height (which is well correlated at its turn with dynamic characteristics like fundamental natural periods).

It may be recognized, on the basis of experience at hand, that this kind of differentiation of categories of buildings is relevant from the viewpoint of seismic vulnerability.

Seismic action is, as well known, a highly complex entity. This means that, in order to be correct, one should characterize it by a complex system of parameters. A discussion on this subject is presented in (Sandi, 2007). This is

unfortunately (at present) not in best agreement with practical feasibility, due to at least two main reasons:

- difficulties of working with such a complex system;
- lack of appropriate basic data, to cover the information required by the adoption of such a system.

As a consequence of this situation, the practical solution widely adopted in various applications is that, of characterizing the seismic action by means of a single scalar parameter, which may have the sense of seismic intensity, or of some reference kinematic parameter of ground motion. The scalar parameter adopted (which may behave like a random variable) will be denoted by Q, while its possible values will be denoted by q. Moreover, due to pragmatic reasons, these possible values will be discretized as q_j (e.g.: integer intensity degrees, or a row of values of some kinematic parameter organized as a geometric progession).

According to knowledge of structural dynamics applied to the case of earthquake action, it turns out that the spectral characteristics of ground motion play a major role in determining its destructive potential upon structures having at their turn various dynamic characteristics. A classical development in this sense is represented by the theory of linear response spectra. A more in depth analysis in this sense shows that destructive earthquake effects do not always best corrrelate with parameters like global intensity, peak ground acceleration, peak ground velocity etc. A much better correlation is reached in case of using response spectra. Given this fact, some results of studies concerning alternative definitions of seismic intensity on the basis of instrumental data (Sandi & Floricel, 1998) were used.

To be more specific, among the variants referred to, a startpoint adopted in order to define the parameters q characterizing the earthquake action severity, was represented by the linear response spectra for absolute accelerations, $s_{aa}(T, \xi)$, and for absolute velocities respectively, $s_{va}(T, \xi)$, related to a reference fraction of critical damping, $\xi = 0.05$. Based on developments of (Sandi & Floricel, 1998), a *spectrum based intensity* q (T), related to a certain oscillation period T, considered for a definite direction of motion, was defined as

$$q(T) = \log_b [s_{aa}(T, \xi) \times s_{va}(T, \xi)] + a \tag{2.1}$$

(where a value $\xi = 0.05$ is used for the fraction of critical damping) while a similar intensity parameter $q^{\sim}(T', T'')$, averaged upon a definite spectral interval (T', T''), for the same direction of motion, was defined according to the averaging rule

$$q^{\sim}(T', T'') = \log_b \{ [1 / \ln (T''/T')] \times \int_{T'}^{T''} [s_{aa}(T, \xi), \times s_{va}(T, \xi)] \, dT/T \} + a \tag{2.2}$$

A rule for averaging intensities of the type defined by Eq. (2.1), corresponding to different (horizontal, orthogonal) directions of motion x and y, is

$$q(T) = \log_b \{[s_{aax}(T, \xi) \times s_{vax}(T, \xi) + s_{aay}(T, \xi) \times s_{vay}(T, \xi)] / 2\} + a \tag{2.3}$$

as given in (Sandi & Floricel, 1998) too. Of course, the averaging rules given by Eqs. (2.2) and (2.3) can be combined, when suitable.

A first calibration of the parameters a and b of previous expressions, aimed at providing a best compatibility with the quantifications of the *MSK* intensity scale (IRS, 1971) was $a = 7.7$ and $b = 4$. Based on statistical results presented in (Aptikaev, 2005) and on considerations of (Sandi & al., 2006), an alternative solution, considered to be more suitable, was $a = 7.8$ and $b = 8$. In this case, the expression of Eq. (2.1) becomes

$$q(T) = (1/0.9) \times \lg [s_{aa}(T, \xi) \times s_{va}(T, \xi)] + 7.8 \quad \text{(lg: decimal logarithm)} \tag{2.4}$$

This expression appears to be suitable from the viewpoint of results provided, but its use leads to some additional work, since it requires additional computations, in order to determine the response spectra of absolute velocities $s_{va}(T, \xi)$. In order to avoid this additional work,

a relatively simple solution could be that, of replacing the absolute velocity spectra $s_{va}(T, \xi)$ by the relative pseudovelocity spectra $s_{pvr}(T, \xi)$, expressed by

$$s_{pvr}(T, \xi) = s_{aa}(T, \xi) \times T / (2\pi) \tag{2.5}$$

which leads to replacement of the expression of Eq. (2.4) by the shorter expression

$$q(T) = (1/0.45) \times \lg [s_{aa}(T, \xi)] + \\ + (1/0.9) \times \lg T + 6.8 \tag{2.6}$$

Warning: the use of this latter expression for very short periods T leads to underestimate of intensity, because the relative pseudovelocity spectra tend to 0 for very short periods, while the absolute velocity spectra tend to the peak ground velocity in this case. Note also that, in case of very long periods, the absolute velocity spectra tend to zero, while the relative velocity spectra tend to the peak ground velocity.

The potential (adverse) *effects of seismic action*, that are specific to the categories of elements at risk considered (i.e. buildings), may be generally referred to as *damage*. The kind and severity of damage inflicted to a building may be, of course, highly variable from one case to the other. The situation is in some way homologous to that of measures of ground motion severity, referred to before. Due to similar reasons, it will be accepted that damage can be characterized by a scalar (random) variable D, which can take various values d (within a definite range). It will be accepted that the possible values of d are discrete, and that they are quantified into discrete values referred to as d_k, in agreement with the provisions of the *EMS-98* European Macroseismic Scale (Grünthal, 1998). Earthquake experience puts to evidence the highly random nature of damage severity due to a case of incidence of seismic action, at a definite level of severity. This leads to the need of use of probabilistic tools in order to describe vulnerability. The discrete (integer) damage grades vary, according to the EMS scale, from 0 (no damage) to 5 (collapse, destruction). Under these conditions, the seismic vulnerability of a definite category of elements at risk (more specifically, a definite category of buildings) will be characterized, in the simplest situations, by a system of conditional distributions (more precisely, conditional upon the level of severity of ground motion). The distribution of damage grades, conditional upon the severity of seismic action, is characterized basically by a system of conditional distributions $p^{(v)}_{k/j}$. The expected (conditional) damage grade $d_j^{\sim} = d^{\sim}(q_j)$ is given, of course, by the expression

$$d^{\sim}(q_j) = \Sigma_k \, k \, p^{(v)}_{k/j} \tag{2.7}$$

A convenient expression for the conditional probabilities $p^{(v)}_{k/j}$ appears to be the classical binomial distribution used by the Italian school (Dolce, 1984),

$$b(k, n, d_j^{\sim}) = \{ n! / [k! / (n - k)!]\} \times \\ \times (d_j^{\sim} / n)^k (1 - d_j^{\sim} / n)^{n-k} \tag{2.8}$$

(k: discrete index of current damage grade: integer, where $0 \le k \le n$; n: maximum value of k, which is equal to 5, in agreement with the EMS scale; $d_j^{\sim} = d^{\sim}(q_j)$: expected damage grade for an intensity $q = q_j$, where $0 \le d_j^{\sim} \le n$), while

$$p^{(v)}_{k/j} = b(k, n, d_j^{\sim}) \tag{2.9}$$

Plots corresponding to damage probability matrices $p^{(v)}_{k/j}$ obtained in Italy and in Romania are presented e.g. in the Working Group report (Sandi, 1986). The data obtained in Italy present also the deviations between empirical data and the data corresponding to the analytical expression of Eq. (2.9).

An analytical expresssion proposed for the expected damage grade $d^{\sim}(q)$, based on developments of (Sandi & al. 1990) is

$$d^{\sim}(q, q_d, q_s) = (n/2) \times \{1 + \tanh [(q - q_d) / q_s]\} \tag{2.10}$$

where n and q are the same as before, q_d is a parameter close to the design intensity (eventually slightly higher) and q_s is a measure of the scatter, varying from about 1.5 for relatively ductile structures to about 2.5 for relatively brittle structures.

From an academic viewpoint, there are two basic ways of estimating vulnerability:

a) performing appropriate engineering analyses (basically parametric, Monte – Carlo type for various sample input data, followed by statistical processing of outcome);

b) statistical analysis of post-earthquake survey data.

Given the practical limitations to their use, the basic ways referred to as items (a) and (b) should be combined whenever possible. Unfortunately, there are quite seldom practical possibillities of deriving conclusions on the basis of use of these ways, while it becomes necessary to make extensive use of expert judgment. One had to rely, essentially, for practical purposes, on such an approach.

Previous developments concerning seismic vulnerability correspond implicitly to what could be referred to as a classical approach, which is usual in literature and can be characterized as follows:

- it refers to a single, practically instantaneous, event;
- the implications of the cumulative nature of effects of successive earthquakes are not considered.

The reality is obviously more complex and some extensions from the classical approach should be considered, at least theoretically. An attempt to deal with such challenges, presented in (Sandi 1998), can be mentioned in this connection, in relation to the consideration of the *evolutionary vulnerability*, which corresponds to the consideration of the fact that the vulnerabilty of a building affected by some damage is higher than the initial vulnerability (in the "no damage" state) of a same kind of structure. The introduction of the concept of evolutionary vulnerability leads to the need of considering, in relation to a definite seismic event, the *pre-event state of damage d'*, and, also, the *post-event state of damage, d"*. The distributions characterizing the evolutionary vulnerability will be conditional not only upon the ground motion severity parameter, but also upon the pre-event level of damage and can be represented generically by an expression $p^{(v")}{}_{k"/j,k'}$. Some logical conditions concerning the features of the distributions $p^{(v")}{}_{k"/j,k'}$ were presented in (Sandi, 1998). The determination of these generalized distributions involves considerably increased requirements and difficulties as compared to the classical case of distributions $p^{(v)}{}_{k/j}$. As an example, in case one wants to use the approach (b) referred to previously, post-earthquake surveys are to be conducted upon samples of buildings for which a pre-event damage survey had been performed. This involves the need of developing of an adequate system of databases, aimed at covering the current situation of the existing building stock. It is hardly believable that such a large scale action and in-depth surveys will be performed soon in practice, given the inevitable evolution of the building stock determined by the general evolution of the economic life. So, rather simple ways of estimating vulnerability, relying to a high extent on the use of expert judgment, are bound to be used in this field.

Table 2.1.

Damage ratios corresponding to various damage grades

Damage grade	Description of damage	Damage ratio (%)	Central Value
NONE - 0	No, or insignificant non - structural damage	0 - 0.05	0
LIGHT - L	Minor, localized non - structural damage	0.05 - 1.25	0.3
MODERATE - M	Widespread, extensive non - structural damage; readily repairable structural damage	1.25 - 20	5
HEAVY - H	Major structural damage; possibly total non - structural damage	20 - 65	30
TOTAL - T	Building condemned or replaced	65 - 100	100
COLLAPSE - C	Building partially or totally collapsed	100	≥ 100

Coming back to the classical definition of vulnerability, which means neglecting of the concept of evolutionary vulnerabililty, it is appropriate, for some purposes, to consider the earthquake effects not only in terms of the observable, physical, damage grade, but also in economic terms, namely in terms of damage ratio, which represents the fraction of replacement cost involved by the occurrence of physical damage. A possibility of conversion between them is given in Table 2.1 (Whitman & Cornell, 1976).

2.3. Categories of buildings considered

The approach adopted relied primarily on the definition of relevant categories of buildings, that are specific to Romania, considering following criteria of differentiation:

– *M*: material and structural system:
  o M_{1a}: RC frames, with incorporation of some RC shear walls;
  o M_{1b}: large prefabricated RC panels;
  o M_{1c}: buildings of RC frames, with unreinforced infill masonry walls, and buildings of reinforced load-bearing masonry (e.g. small columns and/or RC ring-beams);
  o M_2: unreinforced masonry with RC floors;
  o M_3: unreinforced masonry with wooden floors;
  o M_4: wooden;
  o M_5: adobe or other mud-brick or clay houses;

– *H*: height:
  o H_1: single storey;
  o H_2: 2 - 3 storeys;
  o H_3: 4 - 7 storeys;
  o H_4: 8 - 10 storeys
  o H_5: ≥ 11 storeys;

– *Y*: period of construction:
  o Y_1: < 1945;
  o Y_2: 1945 – 1963;
  o Y_3: 1964 – 1970;
  o Y_4: 1971 – 1977;
  o Y_5: 1978 – 1992;
  o Y_6: > 1992.

Some comments on the categories enumerated:

1. The basic information obtained from NIS (National Institute of Statistics) was organnized according to Table 2.2.

2. The fundamental periods of buildings play an important role in determining the amplitude of seismic loading. They are strongly correlated with the heights of buildiings (not forgetting about the influence of structural systems that is to be considered too). Since response spectra were taken into account and were assessed for various areas of the country (Mohindra & al., 2007) as required for subsequent risk analyses

Table 2.2.

Correspondence between categories used by NIS and those used in the paper

NIS CATEGORY	STRUCTURAL CLASS
Reinforced concrete, pre-cast concrete panel or steel skeleton framed concrete	M1A
	M1B
	M1C
Brick masonry, stone masonry or panel substitutes, made of reinforced concrete (steel/beams) with RC floors;	M2
Brick masonry, stone masonry or panel substitutes, made of wood with wooden floors;	M3
Wood (beams, logs etc.)	M4
Saplings plastered with wet clay, adobe, other materials (e.g. wood pressed panels, rolled mud bricks etc.)	M5

or development of earthquake scenarios, it became necessary to assess also fundamental natural periods for the different categories of buildings, in order to subsequently assess the expected damage grades $d_j^{\sim}$, required for the assessment of vulnerability characteristics $p^{(v)}_{k/j}$ in agreement with the relations (2.6) ... (2.8). The main criteria of differentiation of assessed periods were the criteria *H*, *Y* and *M* defined previously. Starting from data of the Romanian code (MLPAT, 1992) and from some data of literature, it was found that some simplifications in assessing fundamental periods are suitable. A simplified way to assess periods, adopted for the study referred to, corresponded to the values given in Table 2.3.

3. The period of construction plays an important role in determining the vulnerability characteristics, due to the evolution of severity of provisions of the regulatory basis of earthquake resistant design. Milestones to be mentioned in this respect are as in Table 2.4.

Table 2.3.

Fundamental natural periods adopted for vulnerability assessment

Period of Construction	Category	*H1*: 1 storey	*H2*: 2 - 3 stories	*H3*: 4 - 7 stories	*H4*: 8 -10 stories	*H5*: ≥11 stories
Pre - 1946	*M1A*	-	-	-	-	-
	M1B	-	-	-	-	-
	M1C	0.159	0.455	0.632	0.981	1.430
1946 - 1977	*M1A*	0.052	0.132	0.308	0.453	0.538
	M1B	0.047	0.111	0.251	0.376	0.434
	M1C	0.156	0.446	0.617	0.954	1.385
1978 - 1992	*M1A*	0.050	0.125	0.294	0.434	0.510
	M1B	0.045	0.105	0.239	0.357	0.408
	M1C	0.150	0.425	0.594	0.918	1.326
Post - 1992	*M1A*	0.050	0.125	0.290	0.425	0.500
	M1B	0.045	0.105	0.235	0.350	0.400
	M1C	0.150	0.425	0.585	0.900	1.300

Table 2.4.

Milestones in the evolution of the regulatory basis of earthquake resistant design

Year	Documents endorsed, getting in force
1945	A first instruction by the Ministry of Public Works
1963	First modern code for earthquake resistant design; widely used, as the subsequent ones
1970	Revision of the previous one
1977	Drastic revision of the previous one, following the destructive earthquake of 1977.03.04
1981	New revision, with lesser quantitative influence, but with some methodological improvements
1992	New revision, benefitting among other from the rich instrumental data obtained during the strong earthquakes of 1986.08.30, 1990.05.30 and 1990.05.31 (new zonation, this time bi-parametric)
1996	The same as previously, but last two sections, concerning the evaluation and strengthening of existing buildings replaced

Vulnerability characteristics were assessed using the basic information referrred to in next subsection. Data at hand and expert judgment were combined to this purpose. Vulnerability functions were considered in two alternative formulations: damage grades (as expressed by the conditional distributions $p^{(v)}_{k/j}$ referred to before) and damage ratios (damage ratio: a financial estimate, representing the fraction of replacement cost corresponding to a definite damage grade).

In order to illustrate the features of vulnerability functions developed in agreement with the methodological approach presented in subsections 2.2 and 2.3, two figures developed in view of drafting vulnerability characteristics are shown. They are expressed in terms of damage ratios and correspond respectively to:

- the vulnerability of non-engineered structures of types M3 (masonry without rigid floors), M4 (wooden), and M5 (adobe);
- the vulnerability of structures of types M1a (RC frames, with incorporation of some RC shear walls), M1b (large prefabricated RC panels) and M1c (buildings of RC frames, with unreinforced infill masonry walls, and buildings of reinforced load-bearing masonry).

In order to use in calculations the data on vulnerability at hand, it is appropriate, of course, to convert them into discrete data.

2.4. Basic information on vulnerability

The first basic data on vulnerability at hand were obtained on the basis of the post-earthquake survey performed in Bucharest subsequently to the 1977.03.04 earthquake on a sample exceeding 18,000 buildings, located in different areas of the city. The survey made it possible to derive statistical damage spectra for several sub-areas of the city (Bălan & al., 1982). These latter results were processed additionally, leading to vulnerability functions expressed in terms of conditional damage distributions, presented in an EAEE Working Group Report, prepared for the 8-th European Conference of Earthquake Engineering (Sandi & al., 1986). The vulnerability functions referred to were related to eight categories of buildings, covering: adobe type, masonry walls with non-rigid (e.g. wooden) floors of different age categories, masonry walls with rigid (r.c.) floors of different age categories too, taller buildings with r.c. walls (distant or closely spaced), taller buildings with r.c. frames with masonry infill. Note in this connection that the scatter of results corresponding to the conditional damage distributions obtained was in the case of Bucharest lower than what the classical distribution of Eq. (2.8) would predict, most likely due to the relatively high homogeneity of the building samples (or sub-samples) considered. On the contrary, the results obtained in Italy subsequently to the Irpinia

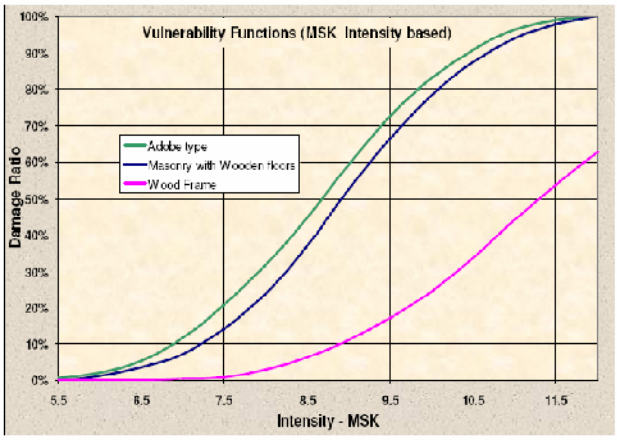

Figure 2.1. Vulnerabililty functions (intensity based on *PGA*) for low rise residential buildings of types M3 (masonry without rigid floors), M4 (wood) and M5 (adobe)

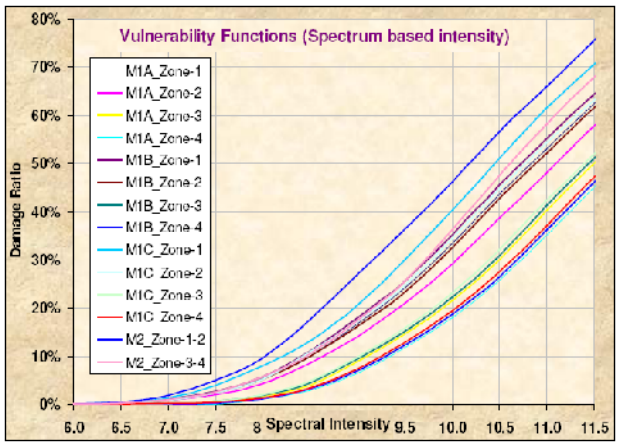

Figure 2.2. Seismic vulnerability functions related to spectrum based intensity, for various seismic zones, for residential buildings of types M1 (RC) and M2 (masonry with rigid floors)

earthquake of 1980.11.24 (Sandi & al., 1986) showed a fair agreement with the scatter predicted by the binomial distribution. Given the lower scatter derived in Romania, a different, generalized, distribution, based on its turn nevertheless on the binomial distribution, was used in risk analyses conducted subsequently (Sandi & Floricel, 1994).

A relevant additional source concerning the vulnerability of buildings is provided by the summary papers (Cişmigiu & al. 1999) and (Colban & al. 1999). The most significant data on vulnerabililty provided in the paper (Cişmigiu & al. 1999) are mostly of qualitative nature. They concern a description of the structural systems of historical religious monuments and the features of the damage they underwent, the same for other monumental buildings and the same for usual buildings (as a rule, residential ones). Some experimental data on the dynamic characteristics were presented too. The most significant data on vulnerability provided in the paper (Colban & al. 1999) are mostly of quantitative nature. Methodological aspects are presented. The basic parameter used in order to characterize vulnerability was the ratio R of actual resistance to resistance required by codes. The ways used for estimating R are described. A sample of 329 buildings was analyzed. Statistical data on age, height and material / structural system were presented. An alternative method, developed in (Mironescu & Bortnowschi, 1983) was briefly presented too. This relies on a simplified determination of S-δ curves. Statistical data on the sample referred to, as related to the different criteria mentioned, were presented. The use of S-δ curves was illustrated too.

Other approaches, like e.g. attempts of THNL analysis, were conducted in a few isolated cases and did not play to date an important role in improving the knowledge of practical relevance concerning the vulnerability of the existing buildiing stock.

An important point raised by the goal of estimating global losses was represented by the determination of the number of buildings of various categories located in various communes. The data provided by the Housing Census of 2002, developed by the National Institute of Statistics, were used in this frame. The data referred to included the total number of dwellings and total floor space in residential dwellings. The data were categorized into 5 material types, 15 age (period of construction) bands and 4 intervals of numbers of stories (single storey to 11 + stories).

3. Use of data and results on vulnerability

A main goal of the activities of vulnerability analysis is that, of providing basic data for risk analysis or for earthquake scenario development. Since a proper, rigorous, risk analysis is not feasible in practice for large systems, earthquake risk scenarios are being developed in the frame of activities referred to.

A main set of data required for estimating expected earthquake inflicted damage and losses is represented by the modelling of seismic hazard. Seismic hazard was estimated in this frame according to the developments of (Mohindra & al., 2007). A second main set of data required for the same purpose is represented by the information on the system of elements at risk (the building stock), concerning an inventory, together with corresponding vulnerability estimates. These data were provided according to the developments of this paper.

The value of total residential exposure in Romania was estimated to be approx. 180×10^9 Euro, out of which the value in urban dwellings is approx. 120×10^9 Euro and in Bucharest is approx. 27×10^9 Euro. Fig. 3.1 shows the distribution of residential exposure for Romania by material class and by height band.

The total earthquake losses based on replacement costs were estimated for each class of building at commune level for each stochastic earthquake event by combining exposure values and damage ratios derived from the corresponding vulnerability functions. Average annual loss (AAL) was computed by combining losses from all stochastic events as

$$AAL = \Sigma\ (Event\ loss \times Event\ Rate) \qquad (3.1)$$

Return period losses were computed for 10, 100 and 250 years from the exceedance probability curve drawn based on modelled losses for the stochastic events. *Loss cost* (*AAL* per 1000 EURO of exposure) was derived as:

$$\textit{Loss cost} = (\textit{AAL} / \textit{Total Exposure Value}) \times \times 1000 \quad (3.2)$$

The modelled average annual earthquake loss, return period earthquake losses and loss cost for residential exposures in Romania were calculated. The distribution of modelled average annual earthquake loss at commune level is shown in Figure 3.2.

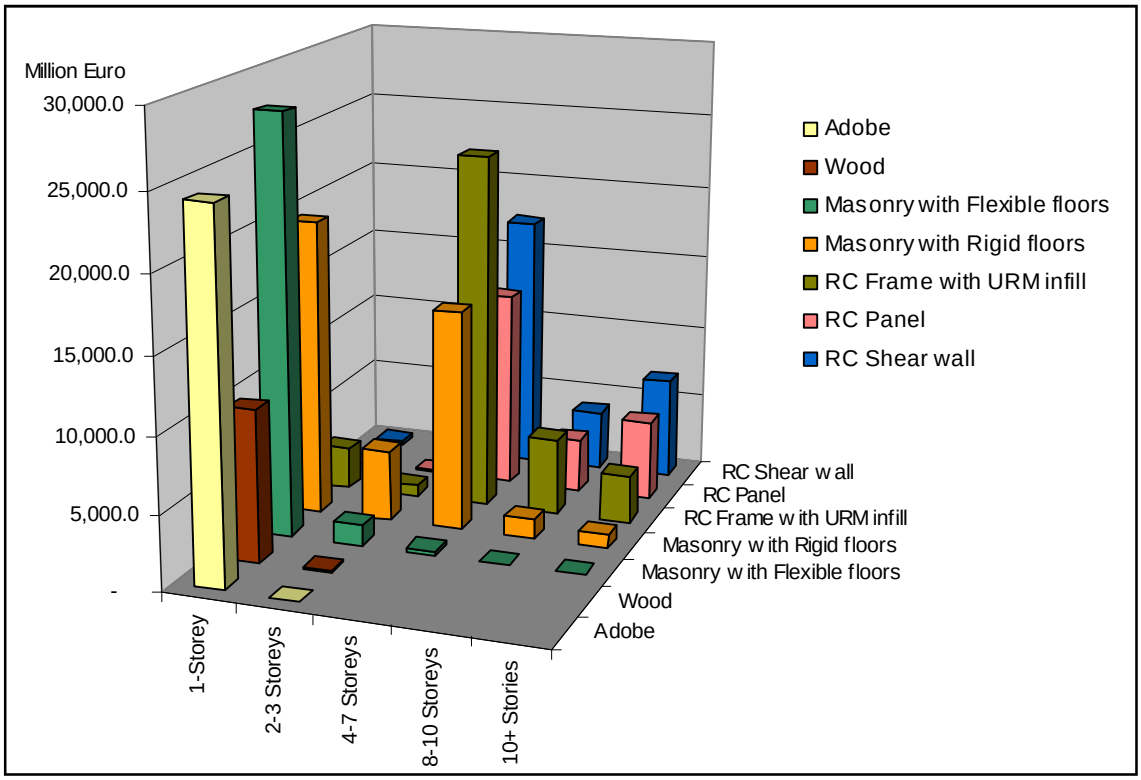

Figure 3.1. Distribution of residential exposure by material class and height band

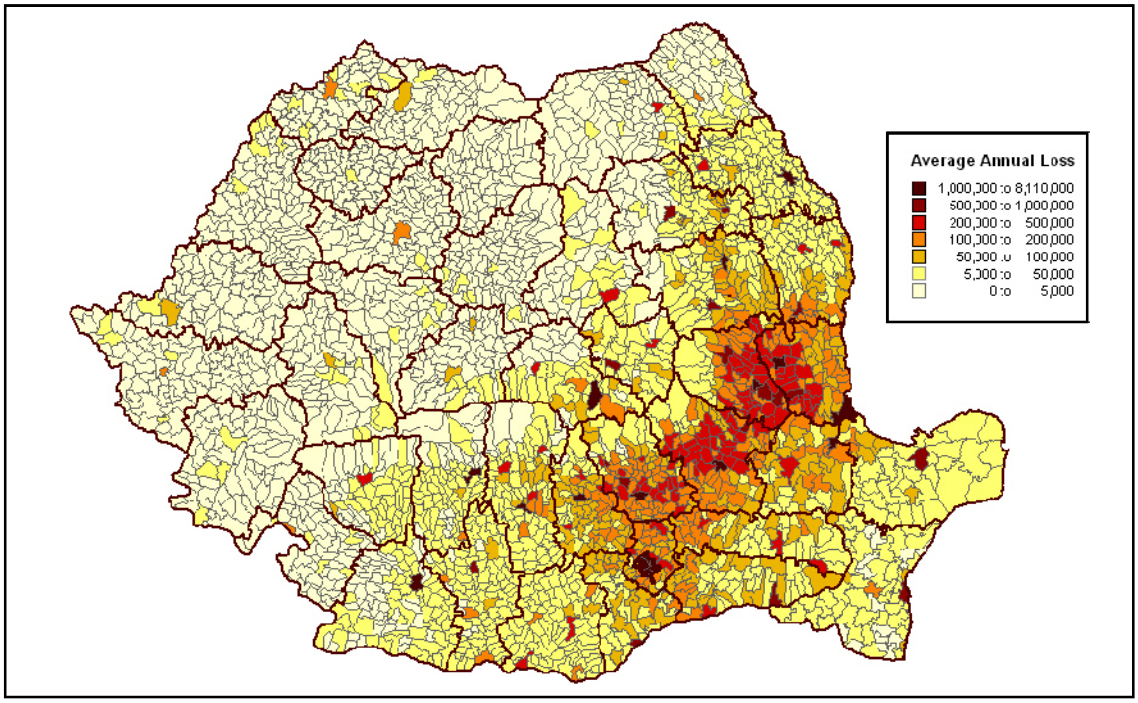

Figure 3.2. Map of Average Annual Loss (AAL) for earthquakes at commune level

4. Final considerations

The developments presented are of interest from at least two viewpoints:

a) presentation of some methodological features concerning the use of the concept of seismic vulnerability;

b) presentation of a first attempt of estimating expected losses at a nation-wide scale.

The methodological developments of the paper presented an attempt of dealing in a consistent way with the problems raised by the definition and estimate of seismic vulnerablity. It is possible, of course, to use other approaches too, but authors believe that the way adopted emphasizes some aspects that are seldom dealt with in vulnerabiliity analyses, while they should not be neglected.

What concerns the estimate of expected losses, which is an issue that often appears to be questionable, it must be recognized that basic input data are negotiable from several viewpoints. This is true especially for the development of earthquake scenarios, but unfortunately cannot be eliminated even for expected losses referring to long time intervals. It is desirable, in this connection, to develop a wide dialog of specialists and to go to some kind of reconciliation, eventually specifying some error margins accepted on the basis of expert judgement.

The concept of vulnerability benefitted to date of quite modest attention in Romania, at least if compared with the situation in more advanced countries (note that Italy is leading by far in Europe in this field). It is high time to change this situation and to enhance the knowledge of engineers in this field as well as the application for various purposes, like those referred to in section 2.1. The development of an appropriate system of databases is a major precondition for projects in this field.

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