Damage Index vs. Instrumental Intensity: A Comparison of Two Different Approaches in Seismic Damage Assessment

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SUMMARY:
The assessment of structural damage due to seismic actions can be performed analytically by using various methods. Two of these methods, derived from very different approaches, are compared in the present paper. The first is based on the evaluation of the instrumental intensity, proposed by Sandi, and which is calibrated to match the values of the EMS-98 intensity scale. The second is based on the use of the spectral values of the Park-Ang damage index, computed for constant values of the strength coefficient, C_y. The two approaches are compared, based on the damage estimations they provide in the case of the moment magnitude $M_w = 7.1$ Vrancea earthquake of August 30, 1986, for various structural typologies existing in Romania at the date of this event and for different locations across the country. Each structural typology is described by structure type, height category and the value of seismic forces used in design, according to the three Romanian seismic codes that were enforced during successive time periods before the event. The computed damage is compared with information on actual damage reported after the earthquake. The overstrength demands imposed by the earthquake are also evaluated, in the damage index approach. The advantages and disadvantages of each approach are shown and conclusions are drawn concerning their future potential refinement.

Keywords: damage index, seismic intensity, intensity scale, EMS 98, Vrancea earthquakes

1. INTRODUCTION

The paper investigates two different approaches in the assessment of building damage due to earthquake loads. The first, based on the instrumental intensity proposed by Sandi (Sandi, 1987, Sandi et al., 1998), uses the background of the EMS-98 macroseismic scale (Grünthal, 1998), combined with the determination of intensity values based on the integration of the square values of spectral acceleration ordinates. The second, based on the use of the Park-Ang damage index, requires a rather detailed knowledge of the structural stiffness, strength and ductility characteristics of the structure.

The study reported in the paper was performed with reference to the August 30, 1986 subcrustal Vrancea earthquake (moment magnitude $M_w = 7.1$, focal depth h = 133 km). In order to analytically assess building damage resulting from this event, 70 horizontal accelerogram components from 35 seismic stations across the country were used. The parameters of the analysis were selected based on the characteristics of the existing buildings in Romania, at the date of earthquake occurrence. Damage maps were generated, according to each of the two above-mentioned approaches.

In order to refine the analysis, twelve reinforced concrete structure typologies, deemed as relevant for the residential building stock of the period, were considered. Each structural typology was described by structure type, height category and code level. Damage was computed for these typologies using both approaches. The analysis was focused on three important cities of Romania, including Bucharest. All results were subsequently compared with information available on the damage actually induced to such structures by the considered earthquake.

2. INSTRUMENTAL INTENSITY APPROACH

2.1. Definitions

The intensity based on destructiveness spectrum, $i_d(\varphi)$, is defined by the following expression (Sandi, 1987, Sandi et al., 1998)

$$i_d(\varphi) = \log_{7,5}\left(\int w_a^2(t,\varphi,0{,}05)\,dt\right) + 6{,}45 \quad (2.1)$$

where $w_a(t,\varphi,\xi)$ is the (absolute) acceleration (m/s^2) for a pendulum of natural frequency φ (Hz) and $\xi = 5\%$ is the damping ratio. The values of the above instrumental intensity are calibrated to match the values of the EMS-98 intensity scale.

In order to assess the destructiveness on separate frequency bands, the intensity in equation (1.1) was averaged upon spectral bands, (φ', φ"), the averaging rule being described by the following equation:

$$i_d{}^*(\varphi',\varphi'') = \log_{7,5}\left\{\frac{1}{\ln(\varphi'',\varphi')}\int\left[\left(\int w_a^2(t,\varphi,0{,}05)\,dt\right)\frac{d\varphi}{\varphi}\right]\right\} + 6{,}45 \quad (2.2)$$

The above formulas were recently improved by comparison with their earlier versions, by modifying the base of the logarithm to 7.5, following the proposal of Sandi, Aptikaev et al. (Sandi et al., 2010).

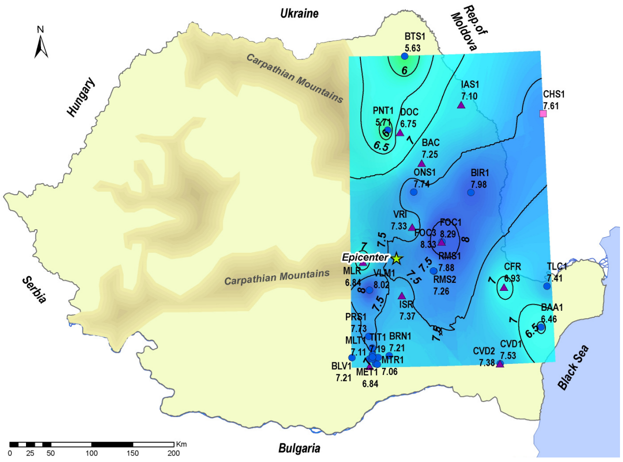
The analysis was related in principle to the 36 dB frequency band (0.25 Hz…16.0 Hz), adopted as a reference, divided into twelve 3 dB subintervals. The Id12 intensity values calculated for these 12 subintervals were denoted, in order, by Id121, Id122 … Id1212. Six of these intervals, considered as characteristic for a large part of the frequency range of the building stock in Romania were studied, as shown in Table 2.1. For compatibility with the second approach used in the study, frequency intervals were expressed as period intervals, with values rounded to the 2nd decimal. Results obtained by using other frequency intervals and/or instrumental intensity expressions have been presented in previous publications (Sandi and Borcia, 2010; Sandi et al., 2011; Craifaleanu and Borcia, 2010, 2011a and 2011b).

Table 2.1. Symbols used to denote averaged instrumental intensities and corresponding frequency / period intervals considered in the study

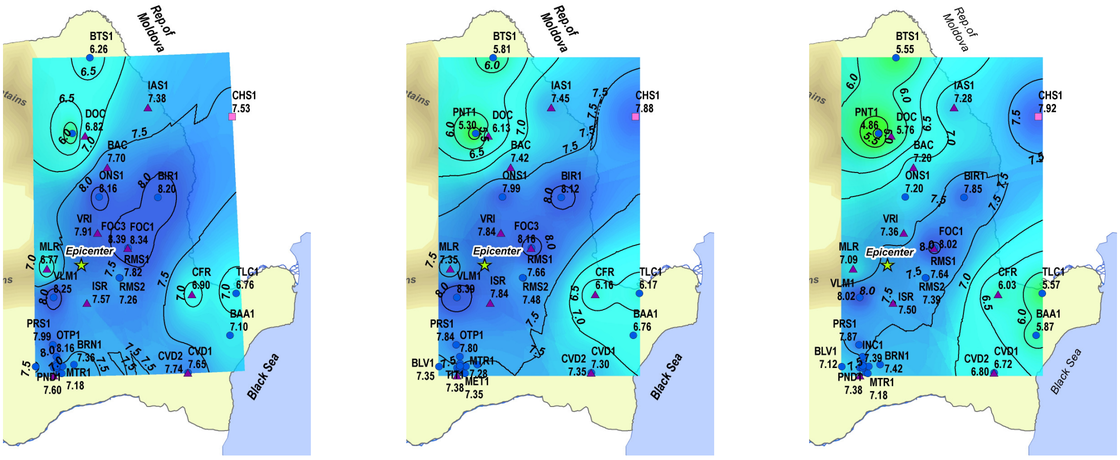
Interval no.	Symbol	φ′ (Hz)	φ″ (Hz)	T′ (s)	T″ (s)
1	Id124	0.71	1.00	1.40	1.00
2	Id125	1.00	1.41	1.00	0.70
3	Id126	1.41	2.00	0.70	0.50
4	Id127	2.00	2.83	0.50	0.35
5	Id128	2.83	4.00	0.35	0.25
6	Id129	4.00	5.66	0.25	0.18

2.2. Instrumental intensity maps

The average instrumental intensity values were computed for the 70 accelerograms considered in the study and the maximum values obtained at each station were mapped, for the selected period intervals. Maps generated for intervals 2 to 5, arranged in the increasing order of period values, are presented in Fig. 2.1. A detailed analysis of the damage reflected by this type of maps, for intervals 1 to 4, can be found in (Craifaleanu and Borcia, 2011a).



a) $T = 0.25\ldots0.35$ s (Id128)



b) $T = 0.35\ldots0.5$ s (Id127) c) $T = 0.5\ldots0.7$ s (Id126) c) $T = 0.7\ldots1$ s (Id125)

Figure 3.1. Instrumental intensity maps for the August 30, 1986 earthquake

3. DAMAGE INDEX APPROACH

3.1. Definitions

In this approach, the Park-Ang damage index (Park and Ang, 1985), *DM*, is used. The index is defined by the following relationship:

$$DM = (u_{\max}/u_{mon}) + \beta\left(E_H/F_y u_{mon}\right) \text{ or } DM \cdot \mu_{mon} = \mu_{max} + \beta\left(E_H/F_y u_y\right) \tag{3.1}$$

In the first equation, u_{max} is the maximum deformation demand during the ground motion, u_{mon} is the ultimate deformation capacity of the system under monotonically increasing lateral deformation, E_H is the hysteretic energy, F_y is the yield strength, u_y is the yield deformation and β is a constant depending on structural characteristics, that can be taken as equal to 0.15 (Cosenza et al., 1993). The second equation provides a convenient way of relating damage to the monotonic ductility, $\mu_{mon} = u_{mon}/u_y$, and to the maximum ductility, $\mu_{max} = u_{max}/u_y$.

In order to describe structural damage, the following interpretation of *DM* values is used (Park and Ang, 1987, Teran-Gilmore, 1996, Cosenza and Manfredi, 2000): *DM* = 0.5 is considered as the upper limit of repairable damage; values between 0.5 and 1.0 characterize severe, non-repairable damage, while values larger than 1.0 correspond to structural collapse occurrence. A value of 0.2 is regarded as the upper limit of insignificant damage.

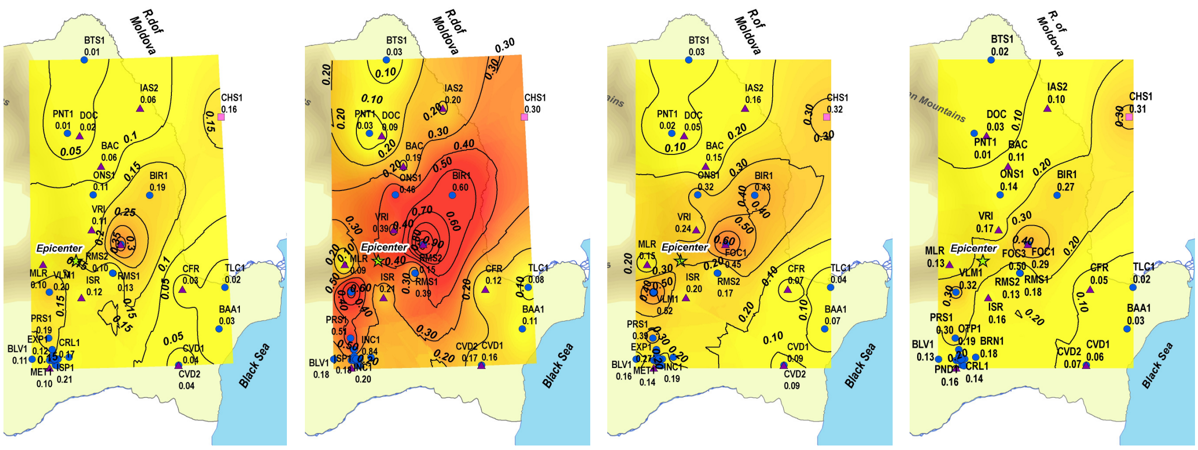
3.2. Damage spectra and damage maps

Spectra of the Park-Ang damage index were computed for the horizontal components of the accelerograms recorded during the considered earthquake. As a parameter of spectral curves, the yield strength coefficient, C_y, defined as

$$C_y = F_y / (mg) \qquad (3.2)$$

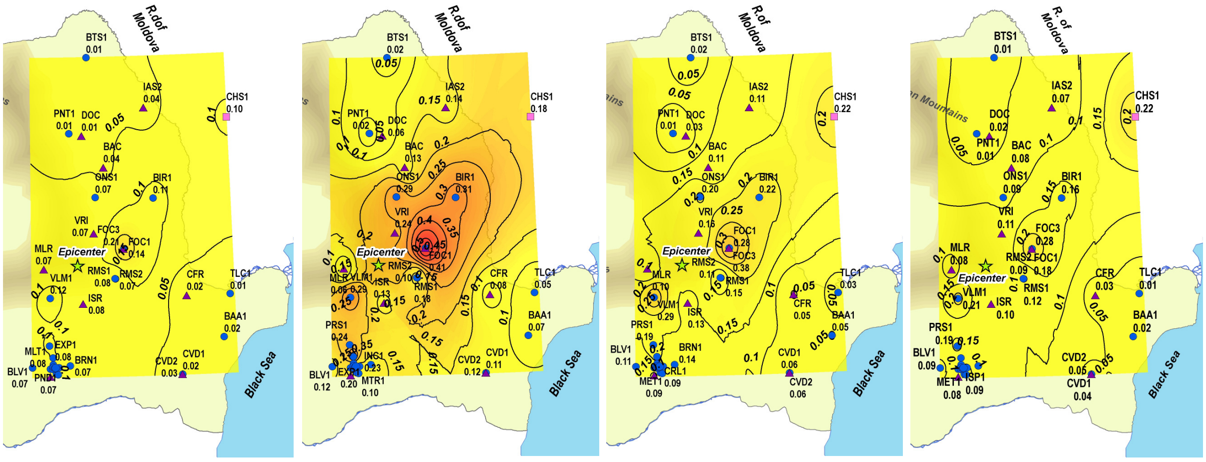
was chosen, where m is the mass of the system and g is the gravitational acceleration. The spectra were determined by considering a bilinear, elastic-perfectly plastic model and a damping ratio of 5%. The C_y coefficient provides a measure of the yield strength of the system and can be quite easily related to the code-specified seismic (base shear) coefficient C_s. By denoting the overstrength factor with R_{OVS}, it can be written:

$$C_y = C_s R_{OVS} \qquad (3.3)$$



a) $T = 0.25…0.35$ s b) $T = 0.35…0.5$ s c) $T = 0.5…0.7$ s c) $T = 0.7…1$ s

Figure 3.1. Damage maps for the August 30, 1986 earthquake. Yield strength coefficient C_y=0.20, maximum monotonic ductility μ_{mon}=6



a) $T = 0.25…0.35$ s b) $T = 0.35…0.5$ s c) $T = 0.5…0.7$ s c) $T = 0.7…1$ s

Figure 3.2. Damage maps for the August 30, 1986 earthquake. C_y=0.30, maximum monotonic ductility μ_{mon}=6

Maps of the Park-Ang damage index spectral ordinates, generated for the strong Vrancea earthquakes of 1986 and 1990 and for different period and yield strength coefficient values, were analyzed in previous studies (Craifaleanu and Lungu, 2008; Craifaleanu, 2009, 2010). For the study presented in this paper, mapped values were computed by averaging spectral ordinates on a number of characteristic period intervals, chosen for compatibility with the damage assessments based on instrumental intensity, presented previously. Examples of the generated maps are shown in Figs. 3.1 and 3.2, for $C_y = 0.20$ and $C_y = 0.30$, respectively, and for $\mu_{mon} = 6$. An analysis of the damage reflected by this type of maps, based on partially different period and C_y values, can be found in (Craifaleanu and Borcia, 2011b). A characteristic feature, which was not discussed in the cited reference, concerns the significantly larger damage values for the T = 0.35…0.5 s period interval. It should be also noticed that damage values decrease below the “repairable” level for the entire analyzed area, if $C_y = 0.30$.

4. ANALYSIS OF DAMAGE FOR CHARACTERISTIC BUILDING TYPOLOGIES

4.1. Building typologies considered in the study

The analysis was focused on blocks of flats, based on standard designs, which were built between 1963 and 1986 (the year of the seismic event considered in the study). The year 1963 was chosen as a reference, as it marks the enforcement of the first compulsory seismic code in Romania, P13-63. Between 1963 and 1986, the Romanian seismic code was substantially revised two times, i.e. in 1970, when the P13-70 code was enforced, and in 1978, after the catastrophic March 4, 1977 earthquake (moment magnitude $M_w = 7.4$), when the P100-78 code was enforced. The seismic macrozonation map of Romania, first enforced in 1952, was also revised in 1963 and in 1977.

The standard blocks of flats form the major part of the present housing stock in the cities of Romania. According to (Bălan et al, 1982), between 1960 and 1977, over 90% of the newly constructed residential buildings were based on standard designs. This trend, characteristic to planned economies, has continued until 1989, ending with the collapse of the socialist regime. As mentioned in the above reference, typical standard structure types before 1977 consisted in reinforced concrete shear walls (RC2) – 60%, precast concrete tilt-up walls (precast concrete panels, RC5) – 23%, masonry (unreinforced / confined) – 13% and reinforced concrete frames (RC3) – 4%. After 1977, multi-storey masonry buildings construction practically ceased, 4 to 5-storey precast concrete tilt-up walls being used instead. The percentage of reinforced concrete frames had a moderate increase, especially for high-rise buildings, and dual systems (shear walls and frames) were introduced as well.

The results provided by the two approaches discussed above were interpreted with reference to the above-described building typologies. As a basis for classification, the typologies defined in the RISK-UE project (Mouroux and Brun, 2006) were used. These are based on structure type, building height and severity of seismic code used in design. The typologies were used either for vulnerability assessment according to the EMS-98 macroseismic scale, in the intensity based approach, or for the assessment of fundamental period and base shear coefficient used in design, in the damage index based approach. Table 4.1 shows building typologies considered in the study.

Table 4.1. Building typologies considered in the study

Structural system	Structure type	No. of stories	Height (stories)	Code level	Typology code
R.C. frames with regular unreinforced masonry infill walls	RC3.1	4…7	MR	LC	RC3.1-MR-LC
				MC	RC3.1-MR-MC
		8…10	HR	LC	RC3.1-HR-LC
				MC	RC3.1-HR-MC
Concrete shear walls	RC2	4…7	MR	LC	RC2-MR-LC
				MC	RC2-MR-MC
		8…10	HR	LC	RC2-HR-LC
				MC	RC2-HR-MC
Precast concrete tilt-up walls (Precast panels)	RC5	4…7	MR	LC	RC2-MR-LC
				MC	RC2-MR-MC
		8…10	HR	LC	RC2-HR-LC
				MC	RC2-HR-MC

4.2. Analysis assumptions and methodologies

For the analysis, all buildings were assumed to have regular vertical and horizontal configurations. Their fundamental periods were determined, consequently, according to the empirical formulas provided by the Romanian codes enforced during the considered time period.

In order to perform damage assessments for different seismic zones, according to the successive macrozonation maps of Romania, three characteristic locations were chosen. These were the cities of Bucharest, Bârlad and Focşani. For all the selected locations, seismic records are available for the 1986 earthquake. Table 4.2 shows seismic intensities specified by codes for these locations. It can be noticed that each of the chosen locations corresponds to a different seismic intensity zone. The only exception is Bucharest, selected for its importance as capital city, and to which, following the great losses caused by the March 4, 1977 earthquake, a higher intensity zone was assigned. Given the large application of standard designs across the country and for the completeness of the study, it was assumed that the above building typologies are present at all considered locations. Also, normal soil conditions were assumed for all locations.

Table 4.2. Seismic intensities specified by Romanian codes for the chosen locations

City	Seismic intensity according to the code:		
	P13-63	P13-70	P100-78
Bucharest	7	7	8
Bârlad	8	8	8
Focşani	9	9	9

For the intensity-based approach, the averaged instrumental intensity was determined for each of the above locations and building typologies, from the corresponding ground motion records, for the interval the structure period. Damage to buildings was then assessed according to EMS-98, based on the averaged intensity value (rounded to the nearest integer) and on the vulnerability classes specified by the European Macroseismic Scale.

For the approach based on the Park-Ang damage index, the values of the yield strength coefficient, C_y, for the considered buildings, are also necessary. The values are difficult to evaluate as, according to Eqn. (3.3), they depend on the available structural overstrength. Therefore, an alternative approach was used in the study, consisting in first determining the base shear coefficients specified by codes and then computing, based on ground motion records, the yield strengths demands (C_y) for specified damage levels. The required overstrength factors, R_{OVS}, can be obtained subsequently, from Eqn. (3.3). Thus, if damage levels used in the analysis are similar to those actually observed for the considered seismic event, the method can be used to estimate the overstrength exhibited by the analyzed structures during that event. Additionally, the method can provide the required overstrength values associated with characteristic damage levels (insignificant, repairable, collapse).

4.3. Results

4.3.1. Instrumental intensity approach

In this approach, damage to buildings was evaluated, for the chosen locations, based on the computed values of the instrumental intensity and according to the vulnerability and damage descriptions in the European Macroseismic Scale, EMS-98. Table 4.4 summarizes the results. Numbers in the table signify damage grades; letters “F” and “M” mean “few” and “many”, respectively; the meaning of the terms is explained in EMS-98. Vulnerability classes specified in the table are the most likely values, according to RMS-98. A preliminary analysis of the results has shown that the best concordance with reported damage is obtained by classifying P13-63 and P13-70 as “moderate level of no earthquake-resistant design (ERD)” (as opposed to the lower category available, “no earthquake-resistant design", which was considered as inadequate) and P100-78 as "high level of earthquake-resistant design". Correspondingly, the values resulting from this classification are given in Table 4.4.

Table 4.3. Damage grades obtained in the instrumental intensity approach. August 30, 1986 Vrancea earthquake, accelerograms: Bucharest INCERC, NS component and Focşani Hotel "Vrancea", EW component

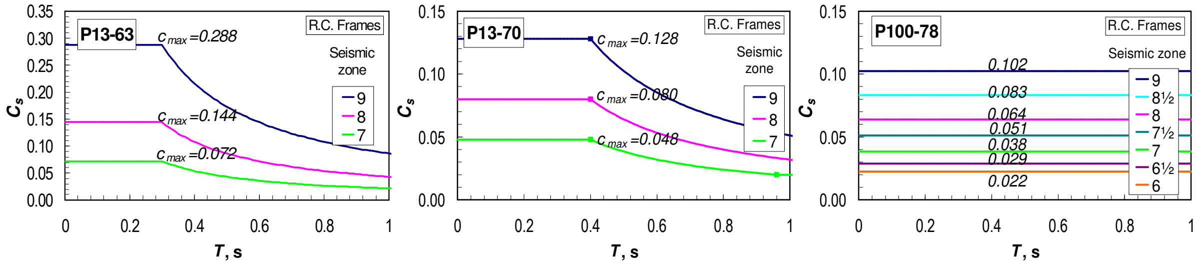
						Bucharest, INCERC, NS component			Focşani, Hotel, EW component		
Structure type	**Typology code**	**Id (according to structural period)**	**Vulnerab. class**	**Id Bucharest**	**Id Focşani**	**P13-63**	**P13-70**	**P100-78**	**P13-63**	**P13-70**	**P100-78**
R.C. frames with regular unreinforced masonry infill walls	RC3.1-MR-LC	Id126	D	7.45	8.01	1F	1F	-	2F	2F	-
	RC3.1-MR-MC	Id126	E			1F	1F	-	2F	2F	-
	RC3.1-HR-LC	Id125	D	7.39	8.06	1F	1F	-	2F	2F	-
	RC3.1-HR-MC	Id125	E			1F	1F	-	2F	2F	-
R.C. shear walls	RC2-MR-LC	Id129	D	6.93	8.15	1F	1F	-	2F	2F	-
	RC2-MR-MC	Id128	E	7.15	8.33	1F	1F	-	2F	2F	-
	RC2-HR-LC	Id127	D	7.46	8.39	1F	1F	-	2F	2F	-
	RC2-HR-MC	Id126	E	7.45	8.01	1F	1F	-	2F	2F	-
Precast R.C. tilt-up walls (Precast panels)	RC2-MR-LC	Id129	D	6.93	8.15	1F	1F	-	2F	2F	-
	RC2-MR-MC	Id128	E	7.15	8.33	1F	1F	-	2F	2F	-
	RC2-HR-LC	Id127	D	7.46	8.39	1F	1F	-	2F	2F	-
	RC2-HR-MC	Id127	E	7.46	8.39	1F	1F	-	2F	2F	-

Due to the impossibility of expressing damage for fractions of intensity degrees in the EMS-98 scale, computed averaged Id values were rounded to the nearest integer, thus obtaining values of 7 for Bucharest and of 8 for Focşani. Consequently, this led to the uniform values in Table 4.3. According to the results, when submitted to the considered ground motions, a few buildings in Bucharest would have suffered grade 1 damage and a few buildings in Focsani would have suffered grade 2 damage. For both cities, only buildings designed according to the P13-63 and P13-70 codes would have been affected, while for buildings designed according to P100-78, no damage would have occurred. It should be noticed, however, slightly larger values, in Bucharest, for reinforced concrete frames and for high-rise shear wall and precast panel buildings, as well as slightly larger values, in Focşani, for certain shear wall and precast panel structures.

EMS-98 defines grade 1 damage for reinforced concrete structures as "fine cracks in plaster over frame members or in walls at the base; fine cracks in partitions and infills", while grade 2 damage is defined as "cracks in columns and beams of frames and in structural walls; cracks in partition and infill walls; fall of brittle cladding and plaster; falling mortar from the joints of wall panels". Generally, these descriptions of damage correspond to the actual reported damage for the analyzed cities due to the August 30, 1986 earthquake; however, they are not sufficiently differentiated according to structure type.

4.3.2. Damage index approach

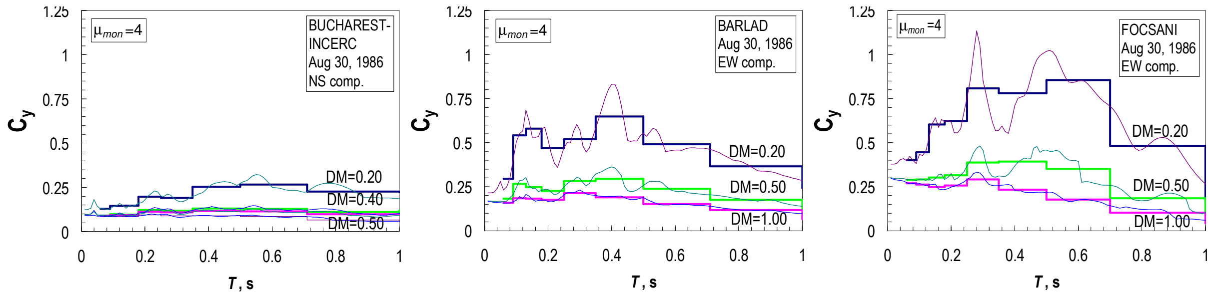
The base shear coefficients, C_s, used in the design of the considered building typologies were computed according to each of the three seismic codes (P13-63, P13-70 and P100-78). As all these codes allowed, for regular buildings up to 10 stories high, the approximation of the deformed shape of the structure under seismic loads by a linear one, the assumption was used for the determination of modal participating mass factors and for the equivalence between multi-degree of freedom (MDOF) and single degree of freedom (SDOF) systems. An example of base shear coefficients computed for reinforced concrete frames is given in Fig. 4.1. The chart abscissas are scaled according to the period range of the analyzed buildings. It is interesting to observe the progressive decrease of base shear coefficients used in design, from P13-63 to P100-78. This decrease was imposed by the government, for economy reasons.



a) P13-63 code b) P13-70 code c) P100-78 code

Figure 4.1. Base shear coefficients, Cs, for reinforced concrete frames, according to three consecutive Romanian seismic codes

The yield strength coefficient, C_y, was computed for different *DM* and μ_{mon} values, by using ground motions recorded on the selected locations during the August 30, 1986 earthquake. The values of C_y were averaged for the same period intervals as those used in the intensity-based approach. Examples of the C_y values obtained by this procedure are given in Fig. 4.2, for $\mu_{mon} = 4$.



a) Bucharest, INCERC station, NS component b) Bârlad, ALA Shelter station, EW component c) Focşani, Hotel "Vrancea" station, EW component

Figure 4.2. Averaging of C_y values, for ground motions recorded at the three locations considered in the study

Of particular interest were considered, with reference to the actual damage caused by the August 30, 1986 earthquake, the results for *DM* = 0.2 (insignificant) and *DM* = 0.5 (repairable). For these values, the overstrength factor, R_{OVS}, was evaluated by the described procedure, by considering $\mu_{mon} = 4$, 6 and 8, respectively. Results obtained for *DM* = 0.2 (with $\mu_{mon} = 8$) for Bucharest and for *DM* = 0.5 (with $\mu_{mon} = 4$), for Focşani are given in Table 4.4, both for $\mu_{mon} = 4$. As shown in the table, P13-63 and P13-70 were classified as low severity codes, while P100-78 was classified as medium severity code. Even if P100-78 prescriptions were more advanced and adequate to the seismicity of Romania than those of earlier codes, its classification as "medium code" is questionable due to the decreased level of seismic forces it specifies.

For Bucharest, as it can be observed from Table 4.4, the largest R_{OVS} values, associated with insignificant damage, were obtained, in Bucharest, for medium- and high-rise reinforced concrete frames, as well as for high-rise reinforced concrete shear walls designed according to the P13-63 and P13-70 codes. The R_{OVS} values were obtained by considering a rather large value for μ_{mon}; for smaller values of the maximum monotonic ductility, overstrength requirements are larger. In what concerns the actual damage that occurred in Bucharest due to the analyzed seismic event, heavy cracking was reported in partition walls for some medium- and high-rise reinforced concrete frames designed according to P13-63 and P13-70. This information is consistent with the values in Table 4.4. However, it should be mentioned that no damage was recorded for shear wall structures, which could mean that they met the overstrength requirements imposed by the earthquake. A similar interpretation can be given to the lack of significant damage (corresponding to *DM*=0.5) to new, post-1963 buildings, reported in Focşani for the same seismic event.

Table 4.4. Average overstrength demands associated to specified damage levels, for the August 30, 1986 Vrancea earthquake. Accelerograms: Bucharest INCERC, NS component and Focşani Hotel, EW component

		Bucharest, *DM*=0.2, μ_{mon} = 8			**Focşani, *DM*=0.5, μ_{mon} = 4**		
		R_{OVS} for buildings designed according to:			R_{OVS} for buildings designed according to:		
Structural system	**Typology**	**P13-63**	**P13-70**	**P100-78**	**P13-63**	**P13-70**	**P100-78**
R.C. frames with regular unreinforced masonry infill walls	RC3.1-MR-LC	3.9	4.4		2.7	4.6	
	RC3.1-MR-MC			1.6			2.7
	RC3.1-HR-LC	3.3	3.8		1.4	2.4	
	RC3.1-HR-MC			1.4			1.4
R.C. shear walls	RC2-MR-LC	1.7	1.7		1.4	2.1	
	RC2-MR-MC			1.1			2.2
	RC2-HR-LC	3.4	2.6		2.3	2.7	
	RC2-HR-MC			1.4			2.3
Precast R.C. tilt-up walls (Precast panels)	RC2-MR-LC	2.2	1.8		1.8	2.2	
	RC2-MR-MC			1.2			2.6
	RC2-HR-LC	2.4	2.0		1.8	2.2	
	RC2-HR-MC			1.4			2.6

The above results are due to a combination of factors, including the shape of the design spectrum specified by the code, the spectral contents of the considered accelerogram, as well as other factors depending on difference between the fundamental period considered in design and the actual period (Mwafi and Elnashai, 2002), the increase of structure periods due to the March 4, 1977 earthquake, for buildings erected prior to this event etc. Further refinement of the analyses presented in this paper could better reflect the influence of each factor.

5. FINAL REMARKS

Two different approaches used in the assessment of building damage caused by earthquakes were applied for the case of the significant Vrancea seismic event of August 30, 1986. The first approach was based on the instrumental intensity proposed by Horea Sandi, while the second was based on the Park-Ang damage index. For each approach, the analysis revealed the spatial distribution of damage for the considered earthquake, as well as detailed results for selected relevant locations and building typologies. The second approach was used also for determining structural overstrength demands imposed by the analyzed earthquake to buildings with various characteristics. Results were interpreted with particular reference to the actual damage reported for the reinforced concrete apartment buildings – most of them based on standard designs – erected in Romania between 1963 and 1990. The study highlighted the advantages and disadvantages of each approach, as well as possible refinements of the analysis methodologies.

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