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Technical benchmarking of the EU harmonized Romanian seismic assessment code

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Professional paper

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Technical benchmarking of the EU harmonized Romanian seismic assessment code

A technical benchmarking study is presented, aimed to evaluate the EU harmonized Romanian seismic assessment code in comparison with its European and U.S. homologues and to identify potential opportunities for its future improvement. The benchmarking procedures are illustrated by parallel seismic assessments, performed, according to the analyzed regulations, on a reinforced concrete frame structure relevant for the building typologies in Romania.

Key words:
technical benchmarking, seismic design code, existing buildings, Eurocode 8

Stručni rad

Iolanda-Gabriela Craifaleanu, Florența-Nicoleta Tănase

Usporedna analiza rumunjskog zakona o seizmičkom ocjenjivanju usklađenog sa zahtjevima EU

U radu se prikazuje tehnička usporedna analiza rumunjskog propisa o ocjenjivanju potresne otpornosti, usklađenog sa zahtjevima EU, u usporedbi s odgovarajućim normama koji su na snazi u Europi i SAD-u, s namjerom da se ustanove mogućnosti daljnjeg razvoja tog propisa. Postupci uspoređivanja ilustrirani su paralelnim ocjenjivanjem seizmičke otpornosti koje je provedeno, u skladu s analiziranim propisima, na armiranobetonskoj okvirnoj konstrukciji usklađenoj s tipologijama građenja koje se koriste u Rumunjskoj.

Ključne riječi:
tehnička usporedna analiza, propis o projektiranju potresne otpornosti, postojeće građevine, Eurokod 8

Fachbericht

Iolanda-Gabriela Craifaleanu, Florența-Nicoleta Tănase

Technische Vergleichsanalyse des mit EU Bestimmungen harmonisierten rumänischen Regelwerks zur seismischen Beurteilung

In der vorliegenden Arbeit wird eine technische Vergleichsanalyse des rumänischen, mit den Bestimmungen der EU harmonisierten Regelwerks zur Beurteilung der seismischen Beständigkeit, im Vergleich zu den entsprechenden Normen, die in Europa und in den USA gültig sind, durchgeführt, um die Möglichkeiten einer weiteren Entwicklung der Normen einzuschätzen. Das Vergleichsverfahren ist anhand paralleler Beurteilungen der seismischen Beständigkeit illustriert, die an einer die rumänische Bauweise vertretenden Stahlrahmenkonstruktion, gemäß den analysierten Normen, durchgeführt worden sind.

Schlüsselwörter:
Technische Vergleichsanalyse, Regelwerk zur Auslegung von Bauwerken gegen Erdbeben, bestehende Bauten, Eurocode 8

1. Introduction

1.1. Regulatory background

At present, two main regulations in the field of the seismic assessment of existing buildings are in force in Romania: the national code, P100-3/2008 [1], completely harmonized with European standards, and Eurocode 8, part 3 (EN 1998-3:2005) [2], adopted as a national standard and used in conjunction with its National Annex for Romania.

The P100-3/2008 code, enforced on January 1, 2010, provides detailed provisions for the seismic assessment of existing buildings, including also a substantial informative annex dedicated to the seismic rehabilitation of various structure types. The entire body of the code, including examples and comments, totals more than 600 pages.

The National Annex for Romania of EN 1998-3:2005 introduced limited changes with reference to the main body of the European standard, as allowed by the structure of the norm. These were meant mainly to ensure coherence with the limit states specified by the national code and to provide values for some nationally determined parameters.

The application of the harmonized national code, P100-3/2008, whose provisions are compliant with the EC Construction Products Directive, is compulsory in Romania. In what concerns EN 1998-3:2005, according to the European Council Resolution of 7 May 1985 [3], this document does not have a mandatory status, as it is categorized as a standard. Consequently, the provisions of the P100-3/2008 code are mandatory and prevail, for national application, upon those of its European homologue. Nevertheless, the European standard is regarded as a reference regulation, and mentions about its provisions are made in several documents in the field.

1.2. General framework of the research

The research reported in the paper is part of a larger study, dedicated to the improvement of Romanian seismic regulations by the integration of recent progress in the field. The study consisted of two distinct phases, of which the first was dedicated to the code for the seismic design of new buildings, P100-1/2006 [4] and the second to the code dealing with the assessment of existing buildings, P100-3/2008. Technical benchmarking techniques were applied by the assessment of a number of typical new and existing reinforced concrete structures, to evaluate the performance of the national codes in comparison with the corresponding European and U.S. codes.

The study was carried out as a pre-normative research, part of the maintenance / revision cycle of Romanian codes, and was finalized with a list of proposals regarding the potential directions to follow in the short, medium and long term for the development and improvement of the relevant provisions in the field. Some of the results were presented in [5, 6, 7]. Given the considerable extent and the need of such studies, it is expected that, in the future, other similar research will be carried out for other types of structures and to cover additional aspects of the code.

1.3. The benchmarking procedure: steps and objectives

Initially considered as a specific process of organizational management, benchmarking is increasingly used in other areas, such as industrial production [8, 9], as the so-called "technical benchmarking". Benchmarking procedures are also used, in several countries, for the assessment of the performance of codes and regulations. A brief review of the most recent applications in the field can be found in [5]. According to the steps described in [10], the benchmarking procedure consists of the following steps:

1. identifying and understanding the process,
2. setting up the terms of comparison,
3. collecting data,
4. data analysis and identification of deficiencies,
5. planning and carrying out improvements,
6. review.

In terms of the study presented in this paper, technical benchmarking was applied to the evaluation of the Romanian seismic assessment code, by comparison with its homologue European and U.S. prescriptions. A "hands-on" evaluation, performed on a number of real structure examples, was chosen to allow an in depth analysis of the seismic assessment procedures in each code. This was meant to facilitate the identification of similarities and differences, as well as of critical points.

During the benchmarking procedure, positive and negative aspects were recorded, as well as potential improvements of the evaluated code, P100-3/2008.

Among the positive aspects, the following characteristics were considered:

- efficiency in achieving a proper, realistic and reliable seismic assessment of the building;
- use of state-of-the-art concepts and methodologies;
- adequacy or adaptability to the specific needs of the national body of regulations;
- overall clarity, logical coherence of provisions, proper level of detailing (including the availability of comments, examples etc.).

Taking into account the situation of the evaluated code, whose development was completed quite recently, it was envisaged that, rather than negative aspects, in the proper sense of the word, potential improvements would be most probably found, as a result of the benchmarking analysis. It should be mentioned, in this context, that P100-3/2008 was developed by a team of experienced specialists and that its validation was performed through a standardized procedure, including public debates and successive analyses performed by the specialized committees of the Romanian Ministry of Regional Development and Public Administration. Moreover, the harmonization with European standards was an important point in the development of the code. Consequently, the following characteristics were primarily checked in the benchmarking:

- existence of non-conservative provisions;
- insufficient detailing of provisions for various practical situations;
- necessity of adjusting the values of certain parameters, in order to better reflect the relevant phenomenon/behavior /requirement etc.

The scope of the study presented in the following encompasses only steps (i) to (iv) of the benchmarking procedure, given that steps (v) and (vi) pertain to the process of code revision, which is performed in the framework of specific regulatory activities initiated, funded, supervised and approved by the entitled national bodies.

2. Brief overview of the seismic assessment codes considered in the benchmarking analyses

The benchmarking of the P100-3/2008 code was carried out with reference to the following regulations:

- Eurocode 8, part 3 (EN 1998-3:2005) [2], adopted as a Romanian standard as SR EN 1998-3:2005; the provisions of the National Annex for Romania of the standard (SR EN 1998-3:2005/NA:2009) were also considered in the evaluation;
- the U.S. standard for the seismic assessment of existing buildings, ASCE SEI 31-03 [11];
- the U.S. standard for the seismic rehabilitation of existing buildings, ASCE SEI 41-06 [12, 13].

It should be noted that some important elements of the above-mentioned ASCE standards are also included in other U.S. standards, such as the IEBC 2009 model-code [14] and ACI 318-08 [15]. Given the scope of the study, the benchmarking addressed only the analytical aspects of the assessment; thus, issues concerning field inspections and *in situ* and laboratory tests were not discussed.

Some of the main features of the seismic assessment codes considered in the benchmarking analyses presented in the paper are summarized in Table 1.

As it can be observed from the table, the Romanian seismic assessment code, P100-3/2008, includes several notions and concepts from its European homologue, Eurocode 8, Part 3. However, it preserves, at the same time, a quantitative approach based on structural seismic safety degrees, that was used, in a relatively similar form, in the previous edition of the Romanian seismic code, P100-92. Another distinctive feature of the Romanian code is that it uses a three-tier assessment methodology, analogous to that in the U.S. standard ASCE 31-03. Among the main similarities between P100-3/2008 and EN 1998-3:2005, the following should be mentioned:

- the performance-based approach on which both regulations are based;
- the adoption, by the Romanian code, of most of the provisions in Chapter 3 of the European standard, concerning information for structural assessment: general information and history, required input data, knowledge level and confidence factors;
- the distinction between ductile and fragile structural elements, as well as the distinction between force-based and deformation-based approaches.

Regarding the differences between the two regulations, there may be mentioned, among others:

- the use of only two limit states for the assessment of existing buildings, in the Romanian code and in the National Annex to EN 1998-3:2005, instead of three, as specified in the European standard; for coherence, it was considered that the two classes should be defined similarly to those used for new buildings;
- an explicit definition of performance objectives and of corresponding levels of structural/non-structural performance and levels of seismic action; thus, two performance objectives are defined: the basic performance objective and the enhanced performance objective.
- detailed provisions on qualitative and quantitative assessment in the Romanian code (Chapter 5), consisting of general requirements, as well as of provisions for various types of structures;
- three quantitative assessment methodologies, with increasing degrees of complexity: Level 1 (simplified), Level 2 (current) and Level 3 (based on nonlinear analysis procedures), with corresponding checklists and grading systems for various structure types;
- a final classification system, consisting of four seismic risk classes (Rs I, highest, to Rs IV, lowest), to express the state of the assessed building; the classes are established according to the estimated / computed values of three basic indicators: the degree of compliance with seismic conformation requirements, R_1, the degree of structural affectation, R_2, and the degree of structural seismic safety, R_3.
- the absence of the q-factor approach as an analysis method.

3. Methodology

3.1. General prerequisites

In the following, the seismic assessment of an eight-story reinforced concrete frame structure is presented, as an illustration of the benchmarking procedure. The structure, regular in plan and in elevation, is relevant for a large part of the mid-rise housing stock in Bucharest. Designed by the institute "Proiect Bucuresti" (project K21/R), it was widely used in the 1980s for the construction of thousands of apartments in Bucharest [16].

Structural regularity, which is a characteristic feature of the selected structure, and, in general, model simplicity, were explicit prerequisites of the study, aimed to facilitate comparisons and to allow focusing on the major assessment steps of the procedures used in each of the considered codes.

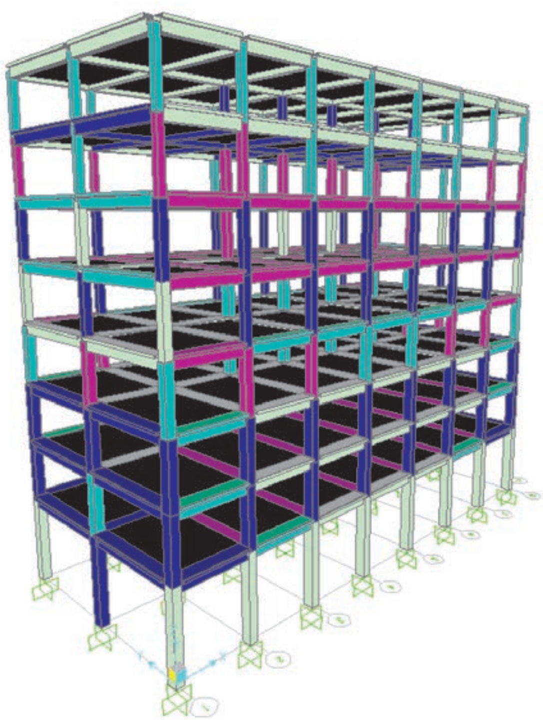

Figure 1. The analyzed RC frame structure

Tshe structure (Figure 1) has seven longitudinal bays of 3.60 m each and two transversal bays of 5.40 m. The ground floor is 4 m high, while the height of the current stories is 2.75 m. All the beams have cross-sectional dimensions of 300 x 550 mm.

The dimensions of exterior columns are 400 x 500 mm at the first story; their cross-sections decrease gradually to the upper stories, reaching 300 x 300 mm at the top story. Interior columns have 500 x 500 mm at the first story, decreasing to 300 x 350 at the top story and having the longer side parallel to the transverse direction of the building. The slab thickness is 120 mm at all stories. In the original design, brick masonry was used for external walls, while partition walls were made of masonry and precast AAC units. These walls have a rather regular distribution. According to [16] and in respect to the objective of keeping the models simple, the contribution of these elements to building stiffness was not taken into account in the calculations.

As information on the original steel reinforcement of the structure was not available, a simulated design was performed according to the relevant Romanian regulations at the time of building construction: the seismic design code, P100-78 [17], and the standard for the design of reinforced and pre-stressed concrete elements, STAS 10107/0-76 [18]. This approach was considered as acceptable for the illustrative and comparative objectives of the study.

Full seismic assessments of the building were carried out according to each considered code, by using linear and nonlinear, static and dynamic analysis methods, as required by the provisions for procedures with different levels of complexity. Details on the analysis methods specified by each code and on their applicability according to the procedure used in the assessment are given in Table 1.

To ensure the coherence of the comparisons, the seismic demands were computed, in all evaluations, according to the provisions of the Romanian code for the seismic design of buildings, P100-1/2006. These provisions are also included in the National Annex for Romania of Eurocode 8, part 1 [19].

For the nonlinear static ("pushover") analysis, two vertical distributions of lateral loads were used, i.e. the "uniform" pattern and the "modal" pattern. In this case, the provisions of the Romanian code, P100-3/2008, are similar to those of the European standard, EN 1998-3:2005.

The seismic action used in the nonlinear dynamic ("time history") analysis was modeled in a simplified way. A real three-component accelerogram was used (the March 4, 1977, INCERC Bucharest record, peak ground acceleration a_g≈0.20g), relevant for the location of the building. The accelerogram was scaled according to the code-specified peak ground acceleration (a_g≈0.24g) and was applied to the basis of the structure in various hypotheses: either as three or two (horizontal) components acting simultaneously or as a single one (the NS component), acting separately on each of the principal horizontal directions of the structure. It should be mentioned that this ground motion record has a particular importance for the seismic and structural engineering in Romania, as it is the single complete accelerogram available from the 7.2-magnitude 1977 earthquake. The NS component of this accelerogram, remarkable by its high spectral amplification at long periods, played a key role in shaping the design spectrum specified, for Bucharest and adjacent areas, for the post-1977 editions of the Romanian seismic design code [20]. This was also extensively used by structural engineers, during the past decades, as a reference action in dynamic nonlinear analyses.

In the current study, identical seismic actions were used for all nonlinear dynamic analyses, since seismic hazard is not relevant as a point of comparison among codes from different countries. The choice of a single, three-component accelerogram was justified by multiple factors, such as: ease of comparing results, compatibility to previous studies and relevance for the city of Bucharest [21]. Given the bilateral symmetry of the building and the special significance of the NS component, the effects of the application of this component as shown above were also investigated.

The structural analyses were performed using programs developed by Computers and Structures, Inc. Providing advanced analysis capabilities, these programs have the advantage of implementing largely-used models and algorithms that are fully compatible with the requirements of all the codes considered in the benchmarking study. A detailed description of their features is given in [22].

As a quantitative criterion for the comparisons between the analyzed codes, the structural seismic safety degree, R_3, which represents the key output of the analytical assessment in the Romanian code, was computed whenever possible, even though this indicator is specific only to P100-3/2008.

3.2. Assessment according to P100-3/2008

The assessment was made by all the three methodologies (Level 1, 2 and 3) specified by P100-3/2008 (see Table 1). It should be mentioned that, according to this code, Level 1 methodology (the simplest) can not be used for the analyzed building, as the acceptance criteria concerning the maximum story number, structure type and maximum peak ground acceleration (PGA) for the location of the building are not satisfied. However, in the presented study, this methodology was applied as well, in order to cover all possible procedures.

Taking into account the available information on the analyzed building, the assessment was performed for knowledge level KL2, with a corresponding confidence factor CF=1.20.

In the analytic approach considered in this study, the assessment according to P100-3/2008 requires the evaluation of the overall degree of structural seismic safety, R_3. This is computed as the ratio between the structural seismic capacity and demand. The R_3 ratio is determined for the ultimate limit state, being expressed in terms of force for Level 1 and Level 2 methodologies and in terms of displacements for Level 3 methodology.

The overall degree of structural seismic safety, R_3, is determined, separately, in terms of force (axial force / shear force / flexural moment) and/or displacement. The minimum resulting value of R_3 represents the final degree of structural seismic safety of the structure. It is important to note, in this context, that the terms of the evaluation differ according to the requirements of each methodology.

In the current study, the assessment was primarily carried out for the basic performance objective (BPO) specified by the code, which consists in complying with the requirements of the *Life Safety* performance level for a seismic action with a mean recurrence interval MRI = 40 years. In terms of the seismicity generated by the Romanian Vrancea subcrustal source, which affects the building location, this means a reduction of PGA to 65 % of the value specified by the P100-1/2006 code for new buildings.

Table 2 shows, for illustration, the minimum R_3 values obtained by the application of each methodology, for the one-component seismic action. The R_3 computed in terms of axial force (P), shear force (V), flexural moment (M), displacement (D) or plastic hinge rotation (θ_{pl}) and base shear force (F) are also provided, wherever applicable. A detailed interpretation of these results was given in [23].

Table 3 shows the establishment of the seismic risk class based on R_3 values, according to P100-3/2008. As it can be observed, the analyzed structure falls, according to the results of all the three methodologies, into the seismic risk class R_s. According to the code, this corresponds to buildings in which major damage can occur for the design earthquake, but in which collapse is less probable.

Figure 2 displays plastic hinges occurring in the analyzed structure at the moment when the maximum computed displacement was attained.

Table 2. R3 values obtained by the application of the three seismic assessment methodologies in P100-3/2008

Degree of seismic safety	Methodology						
	1st Level		2nd Level			3rd Level	
	(P)	(V)	(D)	(V)	(M)	(D or θ_{pl})	(F)
R_3 value	81 %	**58 %**	111 - 138 %	279 % (beams) 265 % (columns)	92 % (beams) **58 %** (columns)	122 %*	55 %*
						>100 %**	**44 %****
	$R_{3,min}$ = 58 %		**$R_{3,min}$ = 58 %**			**$R_{3,min}$ = 55 %*, 44 %****	

* from nonlinear static analysis, ** from nonlinear dynamic analysis

Table 1. Synthesis of the main features of the considered seismic assessment codes

Features	P100-3/2008 – Seismic assessment	EN 1998:3-2005	SR EN 1998:3-2005 & ND for Romania	ASCE/SEI 31-03	IEBC 2009
Performance-based assessment	YES Performance objectives Three performance levels for specified seismic hazard levels	YES · State of damage in the structure - defined based on limit states · Seismic hazard levels - defined based on the mean recurrence interval (MRI) and on the corresponding probabilities of exceedance (EC8-31, Section 2.1)	≡ EN 1998:3-2005	YES	YES
Performance objectives	· *Basic Performance* Objective (performance level: Ultimate Limit State, MRI=40 years) – compulsory · *Enhanced Performance* Objective – for buildings in Rs I and Rs II seismic risk classes (P100-3/2008, Annex A)			According to building performance levels and to seismic hazard levels	Depending on the seismic hazard levels BSE 1 and BSE 2 in ASCE/SEI 41 06 and on the occupancy category in IBC (see IEBC, Tables 101.5.4.1 & 101.5.4.2)
Limit states	1. Ultimate limit state, ULS (life safety requirement) 2. Serviceability limit state, SLS (damage limitation requirement) Note: For ordinary buildings, checking for SLS is not compulsory	1. *Near Collapse* - NC 2. *Significant YESmage* - SD 3. *Damage Limitation* - DL	1. Life safty (≡SD - renamed) 2. Damage limitation (DL) Note: Limit states chosen for compatibility with those for new buildings	1. Life Safety (LS), 3-C 2. Immediate Occupancy (IO), 1-B	1. Life Safety 2. Immediate Occupancy 3. Collapse Prevention
Definition of seismic hazard levels	*Mean Recurrence Interval*: 1. 40 years (P_{50y} = 70 %) 2. 100 years (P_{50y} = 40 %) 3. 475 years (P_{50y} = 10 %) Values of peak ground acceleration (a_g), are specified, corresponding to the above MRI values	Associated to MRI (return period - mean recurrence interval): 1. 2475 years (P_{50y} = 2 %) 2. 475 years (P_{50y} = 10 %) 3. 225 years (P_{50y} = 20 %)	MRI: 1. 100 years (P_{50y} = 39 %) 2. 475 years (P_{10y} = 28 %)	MCE (BSE-2)	BSE-1 & BSE-2 in ASCE/SEI 41 06, or seismic forces reduced to 75% as compared to those in IBC
Knowledge levels	≡ EN 1998:3-2005	YES KL1 (limited), KL2 (normal), KL3 (full)	≡ EN 1998:3-2005	N/A Note: in ASCE/SEI 41-06, Table 2-1, three knowledge levels: Minimum, Usual, Comprehensive	N/A
Confidence factors	≡ EN 1998:3-2005	CF_{KL1} = 1.35 CF_{KL2} = 1.2 CF_{KL3} = 1.0	≡ EN 1998:3-2005	N/A Note: in ASCE/SEI 41-06, a knowledge factor, κ, (0.75 or 1.00) that multiplies member strength capacities, is specified according to knowledge levels & rehabilitation objectives	N/A
Distinction between ductile and fragile structural elements	YES	YES + Primary seismic and secondary seismic elements, according to EN 1998-1:2004 (EC8-3 clause 2.2.1.6(P))	≡ EN 1998:3-2005	YES Deformation/Force-controlled elements ("ductile" / "brittle") + Primary seismic and secondary seismic elements	≡ ASCE/SEI 31-03 & 41-06
Distinction between force-based and deformation-based approaches	YES	YES	≡ EN 1998:3-2005	YES	≡ ASCE/SEI 31-03 & 41-06
Analysis methods	· ELF3, MRS4 with Sd (T) · Nonlinear (static / dynamic) analysis · Lateral force patterns for nonlinear static analysis ≡ EN 1998:3 2005	· ELF, MRS – with Se(T); · nonlinear static / dynamic analysis · the q-factor approach (q=1.5 for R/C structures and q=2 for steel structures does not apply for the LS of Near Collapse Based on the demand/capacity ratios, ρ. For the ELF method: ρ_{max}/ρ_{min}=2.5 (EN 1998:3-2005, Table 4.3)	≡ EN 1998:3-2005 For the ELF method, ρ_{max}/ρ_{min} = 3.0	Depending on the level of investigation (see three-tier procedure below)	According to ASCE/SEI 31 03, ASCE/SEI 41 06 and IBC, Ch. 16 Classification of building structures acc. to ASCE 7, Table 12.2-1

Assessment type	Qualitative and / or quantitative	Quantitative EC8-3, Chapter 4	≡ EN 1998:3-2005	Quantitative	≡ ASCE/SEI 31-03 & 41-06
Seismic assessment methodologies:	Three methodologies: - Level 1 (simplified),, - Level 2 (ordinary buildings) - Level 3 (nonlinear analysis; complex and/or important buildings)	N/A	≡ EN 1998:3-2005	Three-tier procedure (Tier 1, 2 & 3)	≡ ASCE/SEI 31-03 & 41-06
	Level 1 · Applicability: ordinary buildings (according to importance class) with additional conditions (height, regularity, seismicity level) / non-seismically designed buildings / as a preliminary method for more complex buildings · Analysis method: ELF, with S_d (T) – design spectrum · Check ULS only	N/A	N/A	Tier 1 Methodology – Screening phase (compulsory) Checklists for various structure types (Compliant, Non-compliant, Not Applicable); identification of potential deficiencies; LS & IO performance levels Displacement-based Analysis method: ELF, with Se(T) – elastic spectrum	≡ ASCE/SEI 31-03
	Level 2 · For buildings to which Level 1 methodology is not applicable · Displacement-based · Linear analysis: ELF, MRS, with Se(T) – elastic spectrum · Use of displacement amplification factors	N/A	N/A	Tier 2 Methodology – Evaluation phase Displacement-based analysis methods: linear: static – with Se(T) - or dynamic – response is multiplied with the displacement amplification factor URM special procedure method for non-structural elements Requirements for structural elements are divided with ductility-dependent modification factors (m), for displacement-controlled actions	According to ASCE/SEI 31 03, but with seismic forces = 75 % design code forces
	Level 3 · Applied in addition to Level 2 methodology · For important / complex buildings · Nonlinear (static / dynamic) analysis	N/A	N/A	Tier 3 Methodology – Detailed Evaluation Phase For structures that do not meet Tier 2 requirements Linear / nonlinear, static / dynamic analysis Identification of failure mechanism Use of provisions for existing / new buildings, with demand levels multiplied by 0.75	According to ASCE/SEI 31 03 Use of the elastic code spectrum multiplied by 0.75 Spectral values may be amplified by the importance factor, if this is specified by the code Nonlinear analysis methods: according to ASCE 41 06
Assessment of the seismic risk of buildings	Four seismic risk classes, Rs I... Rs IV	-	-	-	-
Indices for establishing the seismic risk class of the building	· R_1 (seismic conformation), R_2 (state of the building), R_3 (seismic safety of the structuree) Given criteria and values of the R indices for Level 1, 2 and 3 methodologies	N/A	N/A	-	-
Decisions for structural intervention	Intervention is necessary if: · $R_3 < 0.65\, a_g$ for Vrancea seismic source · $R_3 < 0.75\, a_g$ for Banat seismic source · (MRI = 40 years)	General criteria (EC83, Ch. 5) Design of structural intervention: recommendations (EC8 3, Ch. 6)	≡ EN 1998:3-2005	-	≡ ASCE/SEI 31-03 & 41-06

[1] EC8-3 = Eurocode 8, Part 3, [2] N/A = not applicable, [3] ELF = equivalent lateral force (analysis method), [4] MRS = modal response spectrum (analysis method)

Table 3. Establishment of the seismic risk class based on R_3 values, according to the P100-3/2008 code

Seismic risk class, R_s			
I	II	III	IV
R_3 (%)			
≤ 35	36 - 65	66 - 90	91 - 100

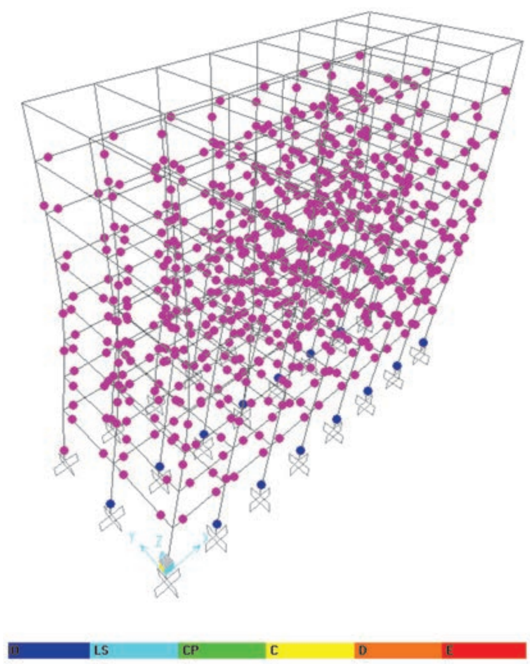

Figure 2. P100-3/2008: Nonlinear dynamic analysis for BPO, plastic hinges at the attainment of the maximum computed displacement

The color coding of plastic hinges in Figure 2 corresponds to the amplitude of plastic rotations. An example of the idealized relation flexural moment (M) - plastic rotation (θ_{pl}) used in SAP2000 [22] to model FEMA356-type plastic hinges [24] is shown in Figure 3. In the figure, point A (grey) represents the origin, point B (magenta) - the yielding point, point C (yellow) - the upper limit of the strength hardening zone, point D (orange) - the residual strength of the cross-section, while point E (red) marks total failure. It is important to note that plastic deformation beyond point B occurs in addition to the elastic deformation, which is not shown in Figure 3. Additional deformation measures, like points IO (Immediate Occupancy - blue), LS (Life Safety - cyan) and CP (Collapse Prevention - light green) are also provided by the program; however, these are only informative.

It should be observed, in Figure 2, the large number of structural elements in which plastic hinges are in the incipient stage, i.e. very close to point B in Figure 3. Due to the inherent approximations in the modeling of nonlinear behavior, yielding may actually not occur in all these elements.

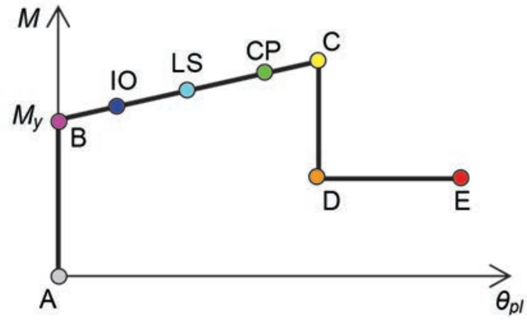

Figure 3. Idealized flexural moment - plastic rotation relation used for plastic hinges modeling

Figures 4 and 5 show other results of the nonlinear dynamic analysis.

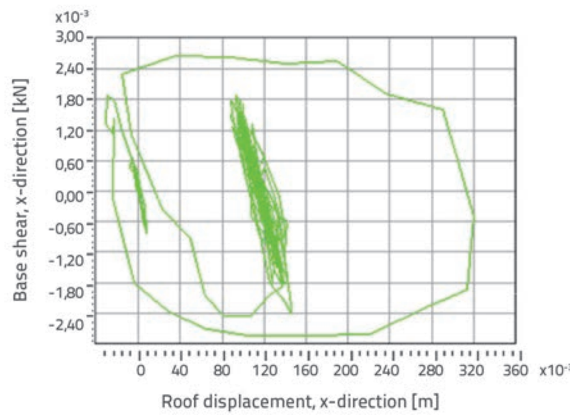

Figure 4. Base shear vs. top displacement (EPO), Longitudinal (X) direction

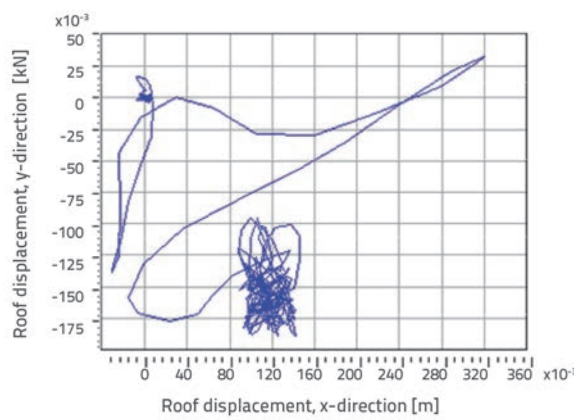

Figure 5. Plan view of the trajectory of a point at the roof level, during the seismic action

The assessment revealed an unfavorable behavior of the structure to seismic actions corresponding to the basic performance objective (BPO). Yielding occurred in several structural elements, as well as significant damage in ground floor columns. The most severe evaluations resulted for the cases in which two or three orthogonal ground motion components were applied simultaneously.

3.3. Assessment according to the European standard EN 1998-3:2005 and to its National Annex for Romania

According to the EN 1998-3:2005, the assessment is based on the evaluation of the demand/capacity ratios of the structure members, ρ_i.

In the first step, the acceptability of using a linear structural model should be verified. For the considered building, large values were obtained for the ρ_{max}/ρ_{min} ratios, (about 6 for beams and greater than 3 for columns). Based on the the code requirements, it resulted that such a model is unacceptable for the analyzed building. It should be mentioned that the maximum value of the demand-to-capacity ratio, to which all elements of the structure should comply, is limited to 2.5 in Eurocode 8, part 3, and to 3 in the National Annex for Romania of the standard.

For nonlinear static analysis, even though a different formula is used in EN 1998-3:2005 to compute the target displacement, the overall verification of the structure in terms of displacement provided results which are very close to those obtained from the assessment according to the Romanian code. In what concerns the verification in terms of strength, the evaluation provided slightly more severe results than the Romanian code, especially due to the differences between the values of the behavior factors used by the two codes. However, this does not change the conclusions on the general state of the building. Namely, by computing R_3 in terms of base shear, a value of 47 % was obtained (that is, smaller then the 55 % resulting from the assessment according to the Romanian code), while in terms of displacement, a value of 128 % was obtained (instead of 122 % according to P100-3/2008). It can be observed that the minimum value of 47 % would classify the building in the Rs II seismic risk class, thus similar to the evaluation according to P100-3/2008.

A notable difference between the Romanian code and the European standard consists in the formulas used for the evaluation of the plastic hinge rotation capacity. For this reason, the verification according to EN 1998-3:2005, in terms of displacement, based on the results of nonlinear dynamic analysis, provided, in general, less severe results as compared to those obtained according to the Romanian code. All plastic hinge rotations were below capacities, thus R_3 values in terms of this quantity were greater than 100 %; however, they were, at the same time, greater than those evaluated according to P100-3/2008.

The assessment based on the q-factor approach revealed deficiencies for beams ($\rho_{max} \approx 6$) and for perimeter columns ($\rho_{max} \approx 3...4$). It is worth noting that this type of assessment resulted in more severe values, in comparison with those obtained from nonlinear analysis.

3.4. Assessment according the U.S. standards ASCE/SEI 31-03 and ASCE/SEI 41-06

The U.S. standard ASCE/SEI 31-03 provides a three-tiered process for the seismic assessment of existing buildings (Table 1). For each methodology, a checklist for identifying structural and nonstructural deficiencies is given. An explicit specification of building performance levels is another notable characteristic of the standard. As mentioned, similar features have been included in the Romanian code, P100-3/2008.

The ASCE/SEI 41-06 standard was included in the evaluation because the differences between it and ASCE/SEI 31-06 point out very clearly the distinct strategies to be used in case only assessment is performed or in case assessment is followed by rehabilitation. Thus, ASCE/SEI 31-03 accepts greater damage levels, for each performance level, in comparison to ASCE/SEI 41-06. This is due to the usual practice of assessing existing buildings with more permissive criteria than those used for the design of new buildings, in order to minimize the requirements to seismically rehabilitate buildings that have relatively small deficiencies with respect to the desired performance level. When the decision of rehabilitation has been taken, the applied criteria are more severe, as those in ASCE/SEI 41-06.

Prior to the rehabilitation process, ASCE/SEI 41-06 requires that an assessment according to ASCE/SEI 31-03 is carried out, to determine if the building, in its existing state, is able to attain the desired seismic performance. Then, the rehabilitation objective is formulated, as a function of the target building performance level, the earthquake hazard level and the objective classification.

It is significant to mention, however, that, at present, the two ASCE standards are planned to be merged into one single document, which will retain the three-tiered approach in ASCE/SEI 31-03 and will use the technical provisions in ASCE/SEI 41-06 as the basis for the analytical procedures [25].

For brevity, only the main conclusions of the evaluations according to the two standards will be presented in the following. The assessment according to ASCE/SEI 31-03 was performed by all three methodologies that this includes. As mentioned, throughout the evaluation, whenever appropriate, R_3-type factors were computed, in terms of the quantities used for assessment in the considered codes. For this reason, quantities used in the calculation of R_3 may differ from a code to another.

In the Tier 1 Methodology, the calculation of R_3 in terms of axial force led to a value of 126 % for the Life Safety limit state, larger than the value of 81 %, computed - by other methods - according to P100-3/2008 (Table 2).

In the Tier 2 Methodology, as flexural moment is used in the assessment, a R_3 value of 150 %, computed in terms of this quantity, was obtained for the beams, while a value of 249 % was obtained for the columns. These substantially larger values, as compared to those resulting from the evaluation according to the Romanian code, are the consequence of the different methods used in the two codes for the computation of strength reduction factors, as well as of the use of the confidence factor, CF, in the Romanian code.

In the Detailed Evaluation Phase (Tier 3 Methodology), a factor of 75 % should be applied to the demands for new buildings (Figure 6).

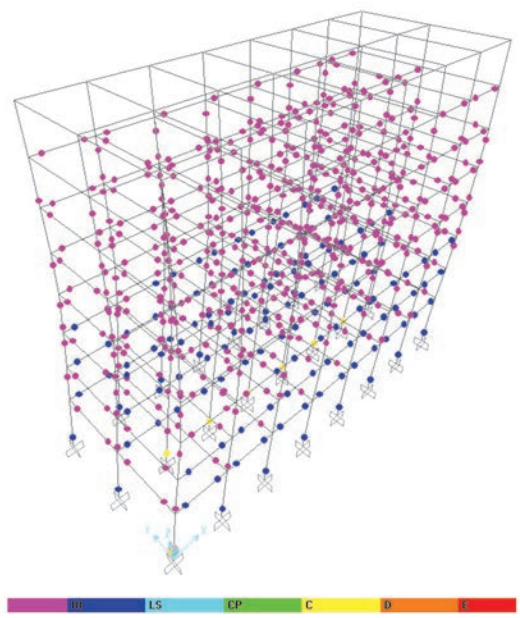

Figure 6. Plastic hinges at the attainment of the maximum computed displacement. Nonlinear dynamic analysis to a seismic action reduced to 75 % of that specified for new buildings

The R_3 factor, computed, in terms of displacement, from the results of nonlinear dynamic analysis, resulted equal to 56 %, thus greater than the 44 % value obtained according to the Romanian code. It should be mentioned, however, that the resulting differences, including the larger plastic deformations, were expectable due to the larger seismic forces required for the evaluation.

Regarding the evaluation according to ASCE/SEI 41-06, it was found that the analyzed building satisfies the criteria that allow its assessment by linear analysis. To get a complete picture of the procedures, the assessment was carried out, however, also by nonlinear static and dynamic analysis.

Strength requirements resulting from linear analysis were higher than those computed according to the Romanian and European regulations, and a value of R_3 of 84 %, computed in terms of flexural moment, was found for the beams, while 53 % was obtained for the columns. On the other part, displacement requirements resulting from nonlinear analysis were lower than those computed according to Romanian and European regulations. An explanation of this fact could reside in the different calibration of displacement amplification coefficients, which appears not to be adequate to the particular seismicity of the building site. Also, significant differences exist in the formulation of verification conditions. For this reason, quantitative comparisons between assessments carried out by Romanian and European standards, on one part, and by American standards, on the other part, should be made with caution.

4. Conclusion

A series of benchmarking analyses were presented, aimed to evaluate the Romanian seismic assessment code in comparison with its European and U.S. homologues and to identify potential opportunities for its future improvement. In the paper, the benchmarking procedures were illustrated by parallel seismic assessments, performed, according to the analyzed regulations, on a real standardized reinforced concrete frame building.

Although, quantitatively, significant differences between the assessments made according to the considered codes were observed in many cases, the general conclusions regarding the degree seismic safety of the analyzed buildings were quite similar. The most significant differences were remarked between Romanian and European codes, on one hand, and U.S. codes, on the other hand.

Regarding the Romanian code, P100-3/2008, there were noted, as positive aspects, the structuring of the assessment methodologies on three levels, following the model of the American standard ASCE/SEI 31-03, the quantification of assessment results by means of seismic safety degrees corresponding to different types of verifications and the classification of buildings in seismic risk classes depending on their overall seismic safety degree. Another positive aspect is the high level of detailing of the code, by the inclusion of a substantial annex dedicated to rehabilitation solutions, and also of extensive comments and examples.

Several needs for short-, medium- and long-term research dedicated to the improvement of the Romanian code and to related subjects were also identified by the benchmarking study. Among these, the quantification of the reliability of performance levels obtained by the current procedures, with potential adjustment of some definitory parameters, the development of a national set of prescriptions on the incremental seismic risk reduction of existing buildings, the development of regulations for existing pre-stressed concrete buildings etc. Part of this research could also contribute, in the future, to the improvement of European standards, by the participation of national specialists to the development of the second generation of Eurocodes.

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