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SEISMIC VULNERABILITY, RETROFITTING SOLUTIONS AND MONITORING FOR EXISTING BUILDINGS

D. Stoica[1]
[1] Technical University of Civil Engineering (UTCB), Bucharest, Romania, stoica@utcb.ro

Abstract: *In Romania (and beyond) most of the existing buildings are made in periods defined as pre-code or low-code (between 80 and 90%). A large typological group study on these buildings may offer a real perspective on the current state of their behavior and vulnerabilities that would show the optimal solution for implementing the best structural intervention to put in safe. Everywhere in the world the old existing pre-code buildings are positioned in the center of the cities so the land is very expensive and the reconstruction of a new modern building seems to be more attractive instead of an expensive retrofitting. Being in countries with high seismic risks and vulnerability or mining subsidence we have the legacy of an existing buildings stock (with masonry and gravitational frame structures) which must became safety from all the viewpoints. Then the monitoring systems for existing buildings, with or without retrofitting seems to be a new interesting idea.*
Keywords: *ductility, vulnerabilities, retrofitting, strategies, monitoring*

1. INTRODUCTION

Because one encompassing study regarding the entire range of existing buildings made in a country over a long period is quite difficult for this paper have used case studies from Bucharest, one of the most seismic vulnerable capitals in the Europe and maybe in the world.
In accordance with HAZUS and FEMA the stock of existing buildings in Romania can be classified according to data presented in Table 1. In the Table 2 and Figure 1 are presented the classification of the existing buildings in Bucharest, according to their period of construction.

Table 1. Existing Buildings Classification

Period and Buildings Type		**Seismic design code**
Buildings type	**Period**	
Pre-code (PC)	Before 1963	Without any seismic design code
Low-code (LC)	Between 1963-1977	P13-63 and P13-70
Moderate-code (MC)	Between 1977-1990	P100-78 and P100-82
Moderate-code to High-code (M-HC)	Between 1990-2006	P100-90 and P100-92
High-code (HC)	After 2006	P100-2006

Table 2. Classification of buildings in Bucharest, according to their period of construction

Number of stories	**Number of buildings**	**Period of construction / Code for earthquake resistance of structures**							
		<1900	**1901-1929**	**1930-1945**	**1946-1963**	**1964-1970**	**1971-1977**	**1978-1990**	**>1990**
≤3	98758	5562	16205	27275	30524	8413	4391	2893	3495
3-7	8159	315	1255	2146	979	804	782	1214	664
≥8	6685	41	95	164	378	645	1072	2854	1436
TOTAL	113602	5918	17555	29585	31881	9862	6245	6961	5595
Percent (%)	100	5.21	15.45	26.04	28.06	8.68	5.51	6.13	4.92
Code type		**PC**				**LC**		**MC**	**M-HC**

From all the studied buildings presented before, some of them are included in the first seismic risk class (RsI) according to the classification made in the Table 3 and presented than in the Figure 1 and figure 2.

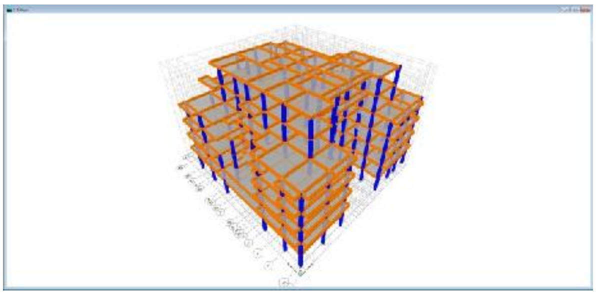
Table 3. Classification of Seismic Risk Classes and Damages

Safety index	<0.35	0.35-0.65	0.66-0.90	0.91-1.00
Romanian Seismic Risk Classes	**RsI**	**RsII**	**RsIII**	**RsIV**
Target Building Performance Levels	**Collapse Prevention Level**	**Life Safety Level**	**Immediate Occupancy**	**Operational Level**
Overall Damage	**Severe**	**Moderate**	**Light**	**Very Light**
General	Little residual stiffness and strength, but load-bearing columns and walls function. Large permanent drifts. Some exits blocked. Infills and unbraced parapets failed or at incipient failure. Building is near collapse.	Some residual strength and stiffness left in all stories. Gravity-load-bearing elements function. No out-of-plane failure of walls or tipping of parapets. Some permanent drift. Damage to partitions. Building may be beyond economical repair.	No permanent drift. Structure substantially retains original strength and stiffness. Minor cracking of facades, partitions, and ceilings as well as structural elements. Elevators can be restarted. Fire protection operable.	No permanent drift. Structure substantially retains original strength and stiffness. Minor cracking of facades, partitions, and ceilings as well as structural elements. All systems important to normal operations are functional.
Non-structural Components	Extensive damage.	Falling hazards mitigated but many architectural, mechanical, and electrical systems are damaged.	Equipment and contents are generally secure, but may not be operable due to mechanical failure or lack of utilities.	Negligible damage occurs. Power and other utilities are available, possibly from standby sources.
Comparison with performance intended for buildings designed under P100-2006	Significantly more damage and greater risk.	Somewhat more damage and slightly higher risk.	Less damage and lower risk.	Much less damage and lower risk.

2. PRE-CODE BUILDINGS

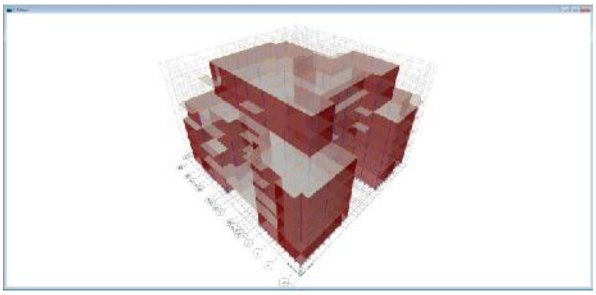
Table 4. – A 7 stories building made in 1946

Structural Model – only RC frames



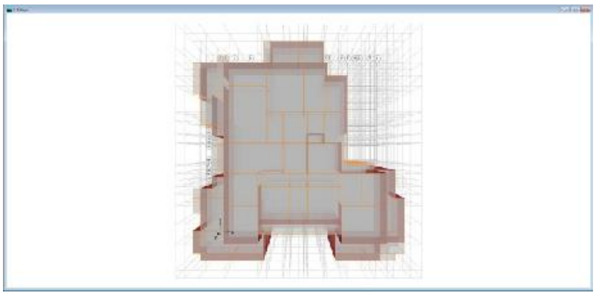
View 1

Structural Model – RC frames and infill masonry

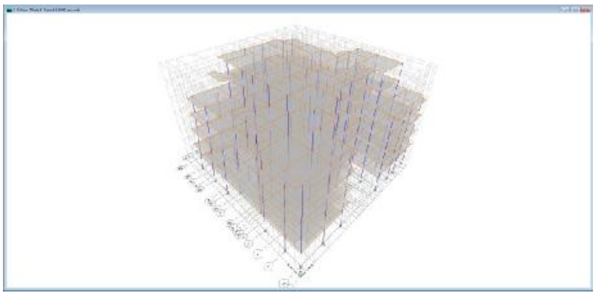


View 1

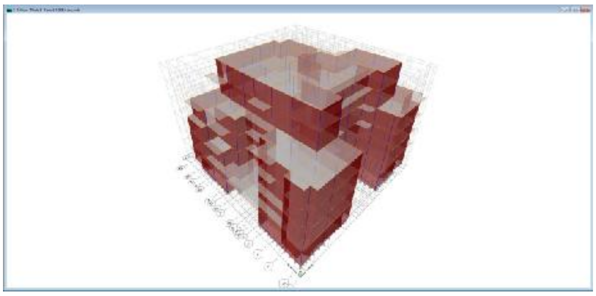
View 2



View 2



Mode 1 – T1=1.094 sec



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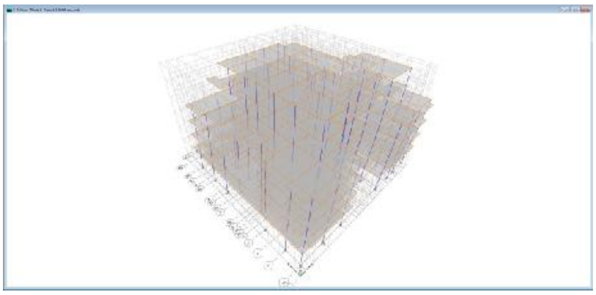

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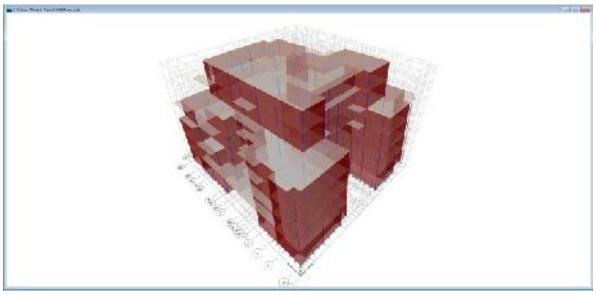

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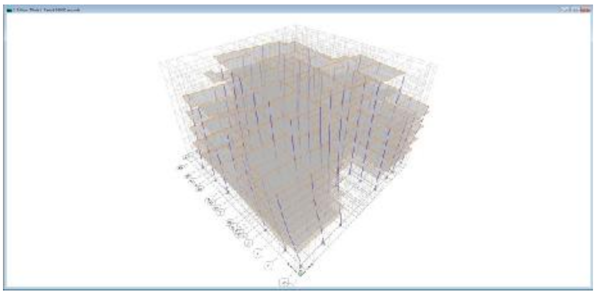
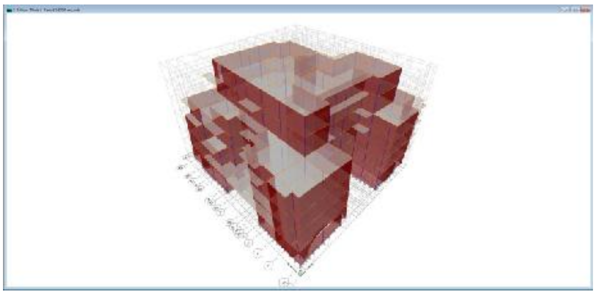


Mode 3 – T3=0.9632 sec



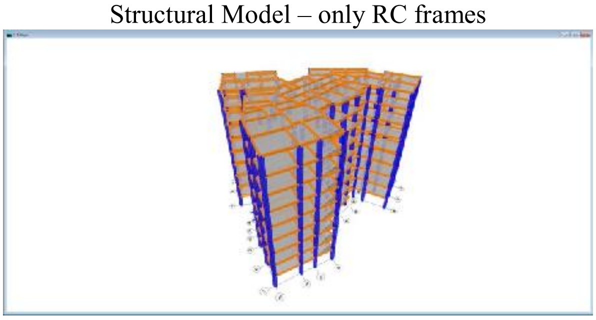
Mode 3 – T3=0.2950 sec

Drift limit = 5‰

Drift x = 25.0‰>5‰	Drift x = 3.5‰<5‰
Drift y = 22.7‰>5‰	Drift y = 2.7‰<5‰
RsI – Seismic Risk Class	RsII – Seismic Risk Class

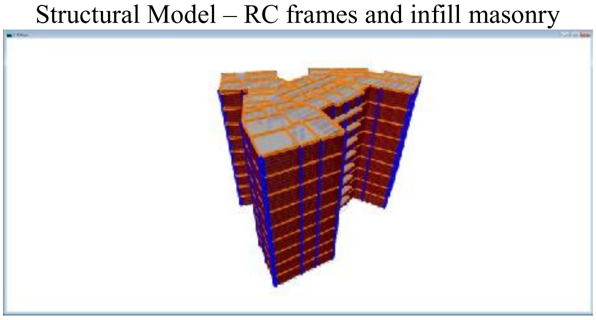
Table 5. – A 9 stories building made in 1936

Structural Model – only RC frames

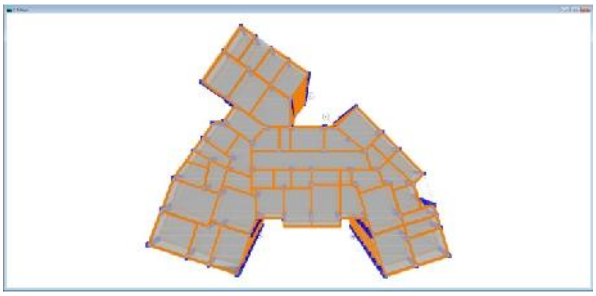


View 1

Structural Model – RC frames and infill masonry

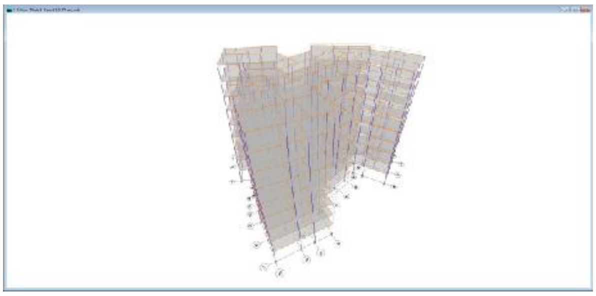


View 1



View 2

View 2



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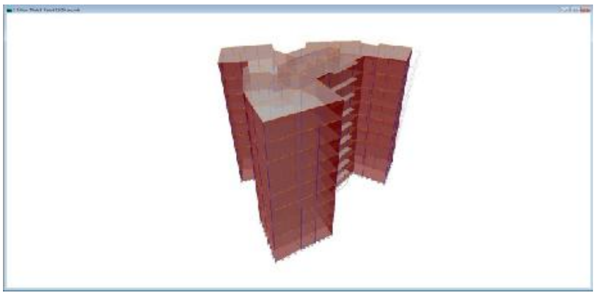
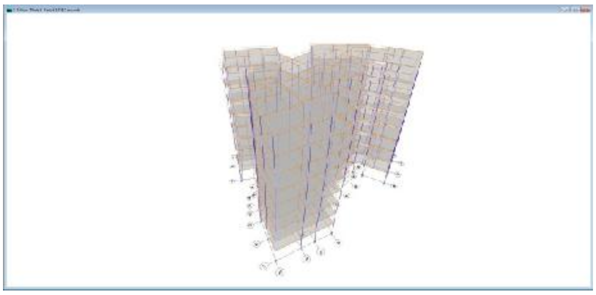


Mode 1 – T1=0.6255 sec



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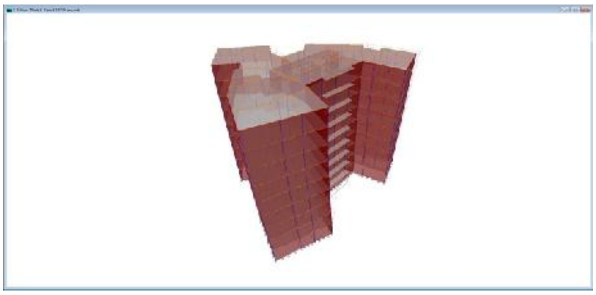
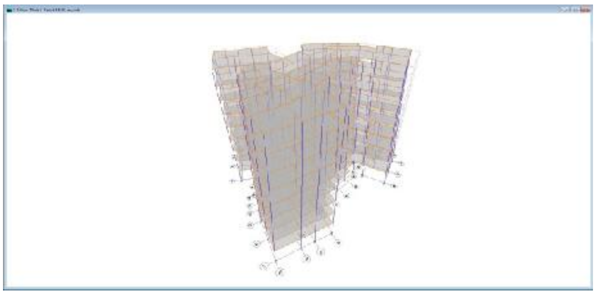


Mode 2 – T2=0.5735 sec



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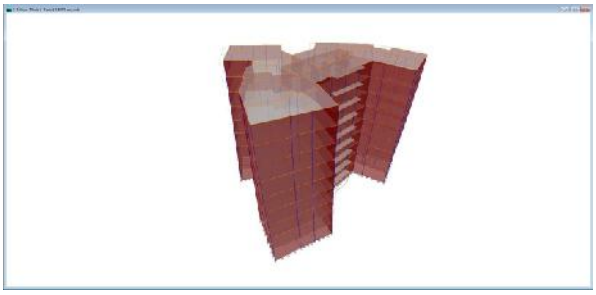

Mode 3 – T3=0.4978 sec

Drift limit = 5‰

Drift x = 60.5‰>5‰
Drift y = 46.0‰>5‰
RsI – Seismic Risk Class

Drift x = 5.0‰<5‰
Drift y = 5.4‰>5‰
RsII – Seismic Risk Class

Table 6. Period of Vibration (seconds)

RC frame structures	RC frame structures with infill masonry	Ratio
1.0940	0.3815	34.9%
1.0640	0.3609	33.9%
0.9632	0.2950	30.6%
2.0179	0.6255	31.0%
1.7512	0.5735	32.7%
1.4102	0.4978	35.3%
2.3061	0.6229	27.0%
2.0787	0.5624	27.1%

Table 7. Drifts (‰)

RC frame structures	RC frame structures with infill masonry	Ratio
25	3.5	14.0%
22.7	2.7	11.9%
60.5	5	8.3%
46	5.4	11.7%
28.75	2.02	7.0%
31	2.48	8.0%
34	9.23	27.1%
34.5	11	31.9%

1.9583	0.5330	27.2%
2.7049	0.9836	36.4%
2.4256	0.8318	34.3%
1.8154	0.5420	29.9%
Average ratio		31.7%

Average ratio	15.0%

One of the most important aspects of modeling the existing buildings is the consideration in analysis of the contribution both in stiffness and strength due to infill masonry walls. As it is shown in the Tables 4 and 5 but also in the Table 6 and 7, the period of vibration decrease with almost 31.7% but also the drift ratio (in ‰) decrease with almost 15% if the models consider or not the infill masonry walls. In this idea one of the most important operations that must be performed in the site is first the visually check of the structural damages (including the infill masonry walls) but also the fundamental period of vibration measurements with specific devices. These will show much better if the infill masonry walls contribution should be considered in the structural modeling. Sometimes because of the building position and neighbor buildings the modeling is very difficult without to take into account all the interaction possibilities between these. But also the retrofitting is not easy to do because normally the pounding must be avoided.

3. LOW-CODE BUILDINGS

The block of flats stock erected between 1963 and 1977 consist of a large palette of functional schemes and constructive solutions mainly resulted from the architectural and urbanity conditions. In that period a great accent were put onto "repetitive design projects" which mean almost 90% of the existing apartment stock. The general behavior characteristics (damages and degradations, assurance level against the partial and total collapse) are determining from the codes deficiencies. The principal applied structural system for multistory buildings used in that period where:

- Large pre-cast RC panels – for 8-9 levels buildings;
- RC frame system with cast-in-place columns, cast-in-place or pre-cast beams and pre-cast slab panels – for 7-15 levels buildings;
- Cast-in-place RC structural walls – for 7-11 levels buildings;
- RC central core and cast-in-place RC columns with cast-in-place or pre-cast beams and slabs – for 11 levels buildings;
- Soft and weak level structures (especially the 1st floor from the commercial reasons) – for 5-11 levels buildings.

From all these collective buildings more than 60% are represented by cast-in-place RC structural walls structural system, then 28% are represented by large pre-cast RC panels structural systems and about 9% for the RC frame structural system. The foremost parameters of the applied constructive systems in the period of P13 aseismic design code are: layout spans and RC structural elements cross section; total weight of the building; base shear force; RC structural walls shear area; compressive centric axial forces in case of RC frame structural systems; minimum percent for the reinforce area; fundamental periods of vibration and mass participation factors. [1-4]
In the studies two idealized buildings types were considered: RC frame structure (Figure 3) and DUAL buildings (meaning a RC frame subsystem and a RC structural walls subsystem) shown in figure 4.

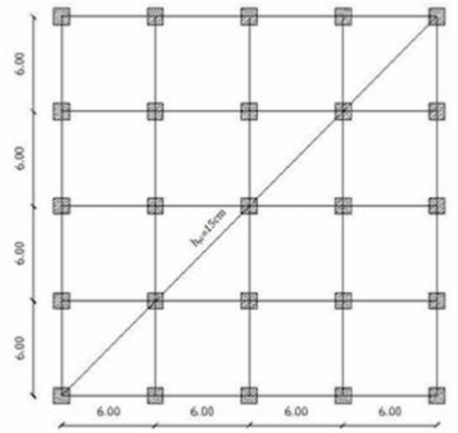

Figure 3. RC frame structures

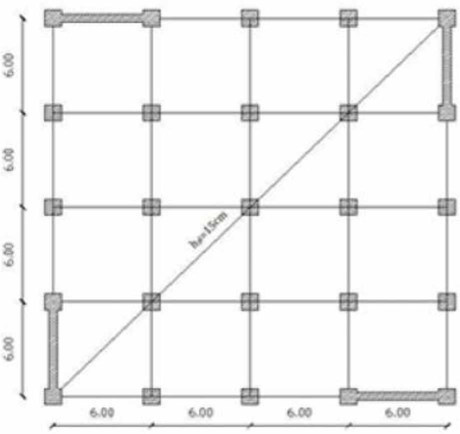

Figure 4. RC DUAL structures

The analyses were made for 2, 4, 6, 8 and 10 stories and in the following tables only the Bucharest seismic zone responses are presented. The conclusions are presented in Tables 8, 9, 10 and in Figures 5 and 6.

Table 8. Periods and Drifts (‰) for P13-63 and P13-70 buildings

Low-code			Number Of Stories									
			P13-63					P13-70				
RC Frame Structures			2	4	6	8	10	2	4	6	8	10
Fundamental Periods of Vibration (sec)	T1		0.32	0.44	0.61	0.77	0.96	0.44	0.61	0.77	0.96	0.96
	T2		0.31	0.44	0.61	0.77	0.96	0.44	0.61	0.77	0.96	0.96
	T3		0.31	0.44	0.59	0.71	0.87	0.44	0.59	0.71	0.87	0.87
DRIFT MAXIM (‰)	a_g=0.24g	x	0.83	0.89	0.81	0.76	0.77	0.6	0.57	0.57	0.76	0.77
		y	0.82	0.89	0.81	0.76	0.77	0.6	0.57	0.57	0.76	0.77
RC DUAL Structures			2	4	6	8	10	2	4	6	8	10
Fundamental Periods of Vibration (sec)	T1		0.09	0.19	0.3	0.44	0.6	0.19	0.3	0.44	0.6	0.6
	T2		0.09	0.19	0.3	0.44	0.6	0.19	0.3	0.44	0.6	0.6
	T3		0.06	0.13	0.21	0.32	0.44	0.13	0.21	0.32	0.44	0.44
DRIFT MAXIM (‰)	a_g=0.24g	x	0.07	0.21	0.38	0.48	0.58	0.31	0.51	0.62	0.48	0.58
		y	0.07	0.21	0.39	0.48	0.58	0.31	0.51	0.62	0.48	0.58

Table 9. Periods and Drifts (‰) for P13-63 and P13-70 buildings

Design Code P100-1/2006			Number Of Stories				
RC Frame Structures			2	4	6	8	10
DRIFT MAXIM (‰)	a_g=0.24g	x	3.44	4.93	6.68	8.51	10.73
		y	3.44	4.93	6.68	8.51	10.73
DUAL Structures			2	4	6	8	10
DRIFT MAXIM (‰)	a_g=0.24g	x	0.27	0.88	1.69	2.84	4.25
		y	0.27	0.88	1.69	2.84	4.25

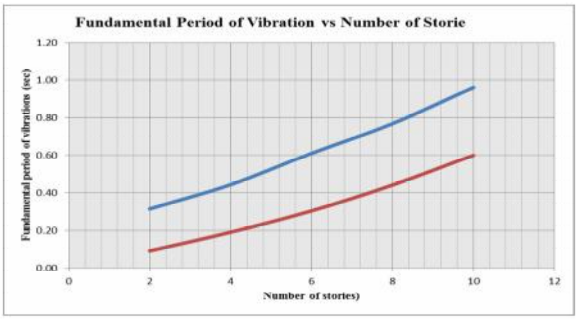

Figure 5. Fundamental periods of vibration

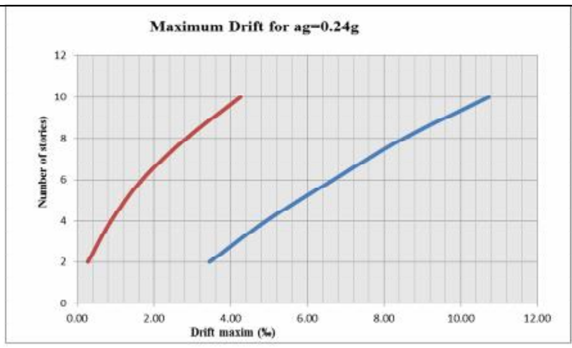

Figure 6. Maximum drifts (‰)

(With red – the RC DUAL structures and with bleu the RC structures)

		Designed with P13-63 Code									Designed with P13-70 Code								
		Drift maxim			Beams Bending Moments			Beams Shear Forces			Drift maxim			Beams Bending Moments			Beams Shear Forces		
RC frame structures	ag	0.16g	0.24g	0.32g	0.16g	0.24g	0.32g	0.16g	0.24g	0.32g	0.16g	0.24g	0.32g	0.16g	0.24g	0.32g	0.16g	0.24g	0.32g
Number of stories	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	4	-	-	X	-	-	-	-	-	-	-	-	X	-	X	-	-	-	-
	6	-	X	X	-	X	-	-	-	X	-	X	X	-	X	X	-	-	X
	8	X	X	X	X	X	X	-	-	X	X	X	X	X	X	X	-	-	X
	10	X	X	X	X	X	X	-	X	X	X	X	X	X	X	X	-	X	X
		Drift maxim			Beams Bending Moments			Beams Shear Forces			Drift maxim			Beams Bending Moments			Beams Shear Forces		
DUAL structures	ag	0.16g	0.24g	0.32g	0.16g	0.24g	0.32g	0.16g	0.24g	0.32g	0.16g	0.24g	0.32g	0.16g	0.24g	0.32g	0.16g	0.24g	0.32g
Number of stories	2							X	X	X							X	X	X
	4	-	-	-	-	-	-	X	X	X	-	-	-	-	-	-	X	X	X
	6	-	-	-	-	-	-	X	X	X	-	-	-	-	-	-	X	X	X
	8	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	10	-	-	X	X	-	-	-	-	-	-	-	X	X	-	X	-	-	-

Table 10. Lacks for P13-63 and P13-70 buildings

4. CONCLUSIONS AND REMARKS

Table 11 - Architectural Characteristics

Pre-code Buildings	Low-code Buildings	
	P13-63	P13-70
Irregularities in plane because of the land shapes; 1-3 blind walls; Interior light yards; Large open spaces; Setbacks on the vertical layouts; Bow-windows; Solid brick walls with 7/14/28 cm; Sometimes appear soft and weak stories.	Generally speaking these types of buildings present more regular layouts, symmetries and seismic gaps. Sometimes appear soft and weak first story, because of the functionality (stores). For the envelope walls the precast panels, cored bricks or cellular concrete were used.	

Table 12 - Structural Characteristics

Pre-code Buildings	Low-code Buildings	
	P13-63	P13-70
The RC frames without regularities and 3D conformation; Beams with multiple bearings and columns bearing onto beams; Every architectural irregularity show a structural irregularity too; Beams were computed as continuous beams and the columns for centrically compression; Poor computation methods (the Cross Method appeared in USA in 1932); The reinforcement were a commercial steel with a low strength; There was not any seismic design code so the bottom reinforcement in the beams decrease in the supports; The beams and columns dimensions were no greater than the masonry dimensions (14, 28 or 42 cm); The base seismic coefficient was less than 2%.	The P13-63 seismic design code was more or less borrowed from the former Soviet Union even there were serious researches in the country to achieve a relevant modern seismic design code; The normalized elastic response spectrum for horizontal components of ground acceleration β had a maximum value of 3 and a corner period around 0.5 sec for the entire Romanian territory The base seismic coefficient as average was about 7%; The RC frame structures because of the structural conformation offer a 3d behavior. The structural RC walls normally had not any reinforcement into the webs.	The P13-70 seismic design code theoretically should improve the P13-63 code but in the reality it reduces first the maximum value of the normalized elastic response spectrum for horizontal components of ground acceleration □ to 2 and the corner period to 0.40; The base seismic coefficient as average was about 5%; The RC frame structures because of the structural conformation offer a 3d behavior. The structural RC walls normally had not any reinforcement into the web excepting eventually the first and the last level, because of other phenomena and not from shear or horizontal slip.

Table 13 - Lacks

Pre-code Buildings	Low-code Buildings	
	P13-63	P13-70
Lack of stiffness; Lack of strength; Lack of ductility capacity; Brittle failure tendency both for beams and columns; Pounding between adjacent buildings.	Rarely less stiffness; Lack of strength especially for structural walls; Less ductility capacity; Because of the seismic gaps the pounding between adjacent buildings is generally avoided.	

Table 14 - Classical Retrofitting Solutions

Pre-code Buildings	Low-code Buildings	
	P13-63	P13-70
Both because of the brittle failure tendency and lack of stiffness and strength the RC jacketing is more or less the main way to put the building in safe. Sometime the implantation of a new structural system (RC structural walls) is necessarily. Every retrofitting solution for the superstructure needs an intervention for substructure and foundation system. These intervention solutions are cumbersome and expensive and often require the eviction of the occupants. Sometimes because of the building position and neighbor buildings the retrofitting is not easy to do. The pounding must be avoided.	Because the gravity safety is satisfy the classical solution may be avoid. However the RC frames or walls may be jacketed in RC solution, to increase especially the strength and sometimes the stiffness.	

Table 15- Modern Retrofitting Solutions

Pre-code Buildings	Low-code Buildings	
	P13-63	P13-70
Because of the RC frame structural system which present weak beams and columns, with brittle failure tendency, without rigid joints the modern solutions using steel frames with bracing or FRP is difficult without initial strengthening of RC elements.	For these types of structures, because of the conformation, the modern retrofitting solutions with steel frames with bracing or FRP are easily applicable.	

Table 16 - Dampers and seismic isolators Retrofitting Solutions

Pre-code Buildings	Low-code Buildings	
	P13-63	P13-70
To use dampers the rigid joints of the RC frames must be assured (ant the existing building does not present this opportunity). The use of tuned mass system is not feasible for this type of buildings, which present lack of gravitational safety for existing columns. To use seismic isolators seems to be an interesting idea but this does not mean that because of the cumulative effects of the previous earthquake on the RC structural elements leads to their consolidation before the base isolation.	Also the use of dampers may be a better solution instead of classical one; To use seismic isolators seems to be an interesting idea because the superstructure had a good conformation and a seismic design code.	

6. STRUCTURAL HEALTH MONITORING SYSTEM

A long-term structural health monitoring system shall include at least five integrated modules/systems: sensory system; data acquisition and transmission system; data processing and analysis system; data management system; structural heath evaluation system. This must include a GPS and an accelerometer system minimum, to obtain the required data. Each device must have a wireless system and a back-up battery in case of energy shut-down. [1-4]

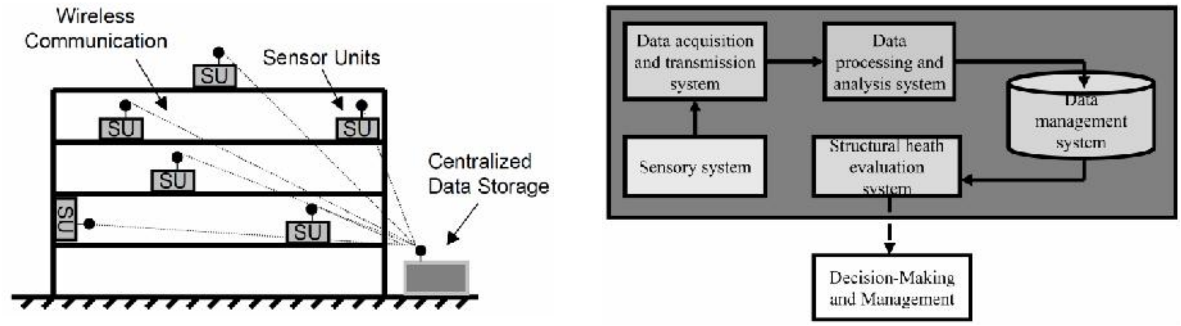

Figure 7 - Active monitoring system (AMS)

Monitor and assess load conditions: examine current design philosophy; verify new analytical methods and computer simulations; assess structural performance and detect damage; facilitate inspection and maintenance works; help authority to make quick and right decision in emergency cases. Ultimate goal is to ensure serviceability, safety, and sustainability

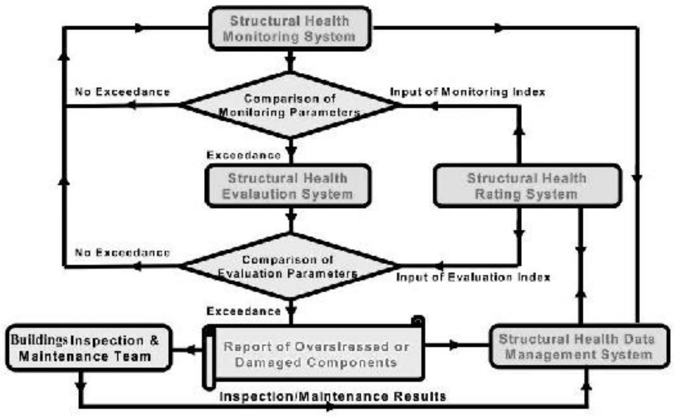

Figure 8 – Structural Health Monitoring System

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