Smart Structures Subjected to Seismic Actions

Gabriel Dănilă[*1], Vlad Petrescu[2], Alexandru B. Cheşcă[3]

[1,2,3]*"Ion Mincu" University of Architecture and Urbanism, Faculty of Architecture. Academiei st., no 18-20, 010014, Sector 1, Bucharest, Romania*

Abstract

After the major earthquakes from Northridge (United States of America) - 1994 and from Kobe (Japan) - 1995, the utilization of the innovative systems to the structural response reduction has an exponential increase. This increase took place due to the behavior of the structures having incorporated innovative devices. The paper presents a comparative study between two seismic isolation systems. The first system is composed of low damping rubber bearings, lead dampers and of steel dampers (LDRB+LD+SD) and the second system is composed of lead rubber bearings and of linear fluid viscous dampers (LRB+LFVD). The study shows that the minimum response – in terms of relative displacements, absolute accelerations, dissipated energies and base shear forces - is obtained for the structure isolated with LRB+LFVD system.

Rezumat

După cutremurele majore din 1994 de la Northridge (Statele Unite ale Americii) şi din 1995 de la Kobe (Japonia), utilizarea sistemelor inovatoare la reducerea răspunsului structurilor a crescut exponenţial. Această creştere se datorează comportării structurilor echipate cu dispozitive inovatoare la aceste cutremure. Articolul prezintă un studiu comparativ între două sisteme de izolare seismică. Primul sistem este compus din izolatori elastomerici cu amortizare mică, amortizori din plumb şi amortizori din oţel, iar al doilea sistem este compus din izolatori elastomerici cu miez de plumb si amortizori cu fluid vâscos liniari. Studiul a arătat că răspunsul minim – în termeni de deplasări relative, acceleraţii absolute, energii disipate şi forţe tăietoare de bază – este obţinut pentru structura izolată cu sistemul format din izolatori emastomerici cu miez de plumb şi amortizori cu fluid vâscos liniari.

1. Introduction

The study make a comparison between different seismic isolation systems. The first system is composed of low damping rubber bearings, lead dampers and of steel dampers (LDRB+LD+SD) and the second system is composed of lead rubber bearings and of linear fluid viscous dampers (LRB+LFVD).

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[*] Corresponding author: Tel./ Fax.: +40744 560 149
E-mail address: gabriel.danila@ymail.com

The lead dampers are made of 99.99% pure lead. Among the advantages of this type of damper there are included: high initial stiffness, to withstand the wind loads; stable hysteretic curve for a large number of cycles; they can be easily inspected and replaces after an earthquake; they does not have corrosion problems; similar behaviour in all horizontal directions; low cost; etc. The disadvantages are: low yielding strength and modest energy dissipated [3].

In Japan there are used two types of lead dampers: U-180 with the maximum estimated horizontal displacement of 600 mm and U-2426 with the maximum estimated horizontal displacement of 800 mm [3].

a)   b)
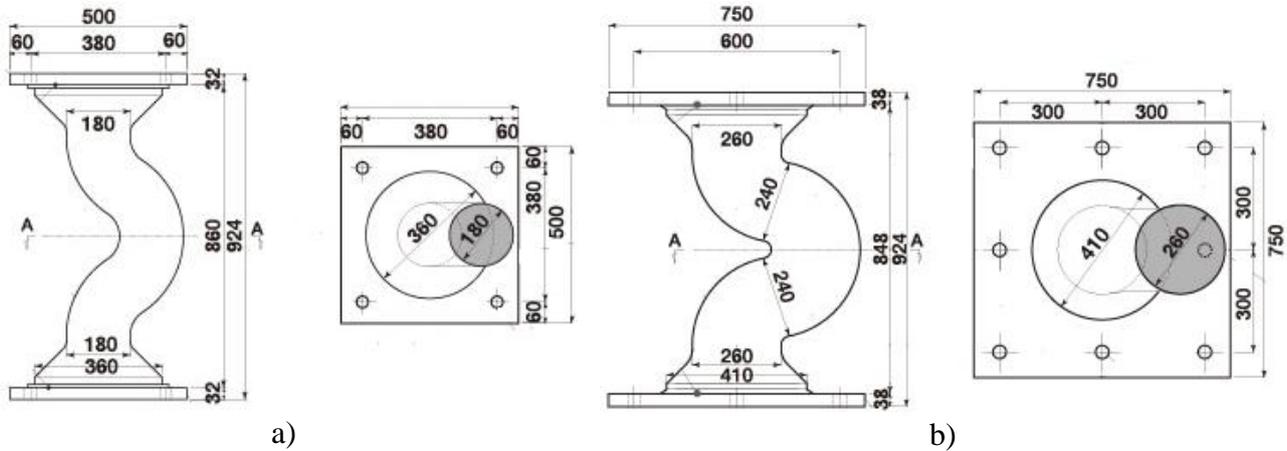
Fig. 1. – Lead dampers [3,6]: a) U-180, b) U-2426

The steel dampers, used in the seismic base isolation are widely used in Japan due to their effectiveness in energy dissipation and low cost. The advantages of this type of dampers are: high yielding strength; stable hysteretic curve for a large number of cycles; they can be easily inspected and replaces after an earthquake; they does not have corrosion problems; similar behaviour in all horizontal directions; low cost; etc. The main disadvantage of this damper is low initial stiffness [3].

Fig. 2. – Spiral steel damper [3,7]

The main objective of the study is represented by the comparison – in terms of displacements (of the isolation systems and of the structure), base shear forces, energy dissipation and accelerations – between two seismic isolation systems.

2. Description of the Analysed Structure and of the Isolation Systems

The analysed structure is a dual structure, with reinforced concrete shear walls and frames on both directions of the building. The location of the building was considered Bucharest city. The height

regime consists of ground floor and eight storeys, with storey height of 2.8m. The building has three spans - the central one of 3m and the marginal ones of 7m – and four bays of 8m.

a)
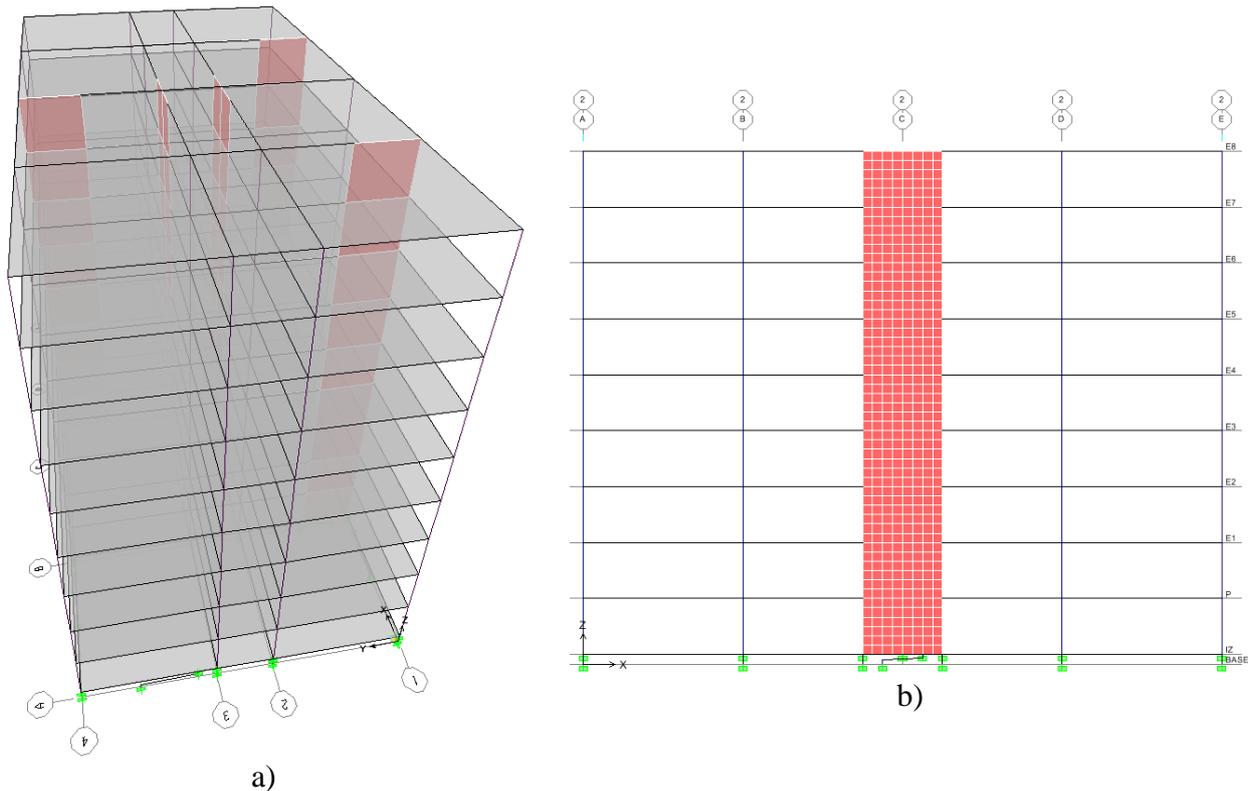
Fig. 3. – The analysed building: a) General view, b) Elevation 2

The analysed building was seismically isolated using two different seismic isolation systems. The first system (LDRB+LD+SD) is composed of twenty-five low damping rubber bearings (one bearing under each column and two bearings under each reinforced concrete shear wall), six U-2426 lead dampers and six TSUD50x4 steel dampers. The second system (LRB+LFVD) is composed of twenty-five lead rubber bearings (one bearing under each column and two bearings under each reinforced concrete shear wall) and twelve linear fluid viscous dampers (six on the longitudinal direction and six on the transversal direction of the building).

3. The Preliminary Design of the two Isolation Systems

The preliminary design of the isolation systems was performed, considering the analysed structure a system with one dynamic degree of freedom. The structure was isolated at a vibration period, T_{is}=3.5s, taking into account a damping ratio of the isolation systems, ξ_{ef}=28%.
The displacement demand of the isolation systems, d_{dc}, to the design earthquake was determined using Eq. (1) [5,9].

$$d_{dc} = \left(\frac{T_{is}}{2\pi}\right)^2 \cdot a_g^d \cdot \beta(T_{is}) \cdot \eta = \left(\frac{3.5}{2\pi}\right)^2 \cdot 0.24 \cdot 9.81 \frac{m}{s^2} \cdot 0.718 \cdot 0.55 = 0.289m \quad (1)$$

where: a_g^d is the ground acceleration corresponding to the design earthquake; $\beta(T_{is})$ is the normalised spectral ordinate, corresponding to the vibration period, T_{is} and η is the damping correction factor.

The effective horizontal stiffness of the lead dampers, k_{ef}^{ld}, to the design earthquake was determined using Eq. (2).

$$k_{ef}^{ld} = n_{ld} \cdot \frac{F_y^{ld}}{d_{dc}} = 6 \cdot \frac{225kN}{0.289m} = 4671.3 \frac{kN}{m} \tag{2}$$

where: n_{ld} is the number of lead dampers and F_y^{ld} is the yield force of the lead damper.

The effective horizontal stiffness of the steel dampers, k_{ef}^{sd}, to the design earthquake was determined using Eq. (3).

$$k_{ef}^{sd} = n_{sd} \cdot \frac{F_y^{sd}}{d_{dc}} = 6 \cdot \frac{271.6kN}{0.289m} = 5638.8 \frac{kN}{m} \tag{3}$$

where: n_{sd} is the number of steel dampers.

The effective horizontal stiffness, k_{ef}^{ldrb}, of the low damping rubber bearings was determined using Eq. (4).

$$k_{ef}^{hdrb} = \left(\frac{2\pi}{T_{is}}\right)^2 \cdot \frac{G_{SC}}{g} - k_{ef}^{ld} - k_{ef}^{sd} = \left(\frac{2\pi}{3.5s}\right)^2 \cdot \frac{65668.16kN}{9.81m/s^2} - 4671.3\frac{kN}{m} - 5638.8\frac{kN}{m} = 11262.8\frac{kN}{m} \tag{4}$$

where: n_{ldrb} is the number of low damping rubber bearings.

The damping constant, C_{lvd}, of the linear fluid viscous dampers was determined using Eq. (5) [1].

$$C_{lvd} = \frac{4\pi \cdot G_{SC} \cdot \xi_{lvd}}{n_{lvd} \cdot T_{is} \cdot g} = \frac{4\pi \cdot 65668.16kN \cdot 13\%}{6 \cdot 3.5s \cdot 9.81m/s^2} = 520.9kN \frac{s}{m} \tag{5}$$

where: G_{SC} is the total weight of the building in the special combination of loads; ξ_{lvd} is the damping ratio of the linear fluid viscous dampers; n_{lvd} is the number of the linear fluid viscous dampers on x and y direction, respectively and g is the ground acceleration.

The effective horizontal stiffness, k_{ef}^{lrb}, of one lead rubber bearing was determined using Eq. (6) [8].

$$k_{ef}^{lrb} = \left(\frac{2\pi}{T_{is}}\right)^2 \cdot \frac{G_{SC}}{n_{lrb} \cdot g} = \left(\frac{2\pi}{3.5s}\right)^2 \cdot \frac{65668.16kN}{25 \cdot 9.81m/s^2} = 862.9 \left[\frac{kN}{m}\right] \tag{6}$$

where: n_{lrb} is the number of lead rubber bearings

4. The Seismic Action

The seismic action is described by six artificial accelerograms compatible with the design spectrum for Bucharest and one recorded seismic motion on INCERC-Bucharest site, corresponding the March 4, 1977 earthquake [4].

The recorded seismic motion was scaled, to the maximum ground acceleration of 0.24g, corresponding to the design ground acceleration for Bucharest, having the mean recurrence interval of 100 years. The artificial accelerograms were generated by means of the SeismoArtif [10] computer program [4].
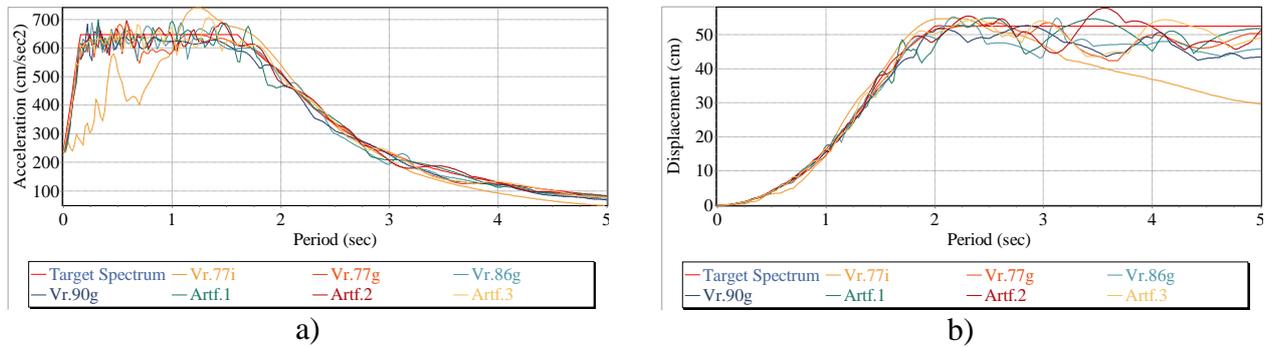
Fig. 4. – The elastic spectra of the seven accelerograms: a) Acceleration spectra; b) Displacement spectra.

5. Nonlinear Time-History Analysis and Comparative Results

The nonlinear time-history analysis of the isolated structure was performed using the SAP2000 v15.1.0 [2] computer program, considering the structural elements and the isolation systems with nonlinear behavior [4].

The devices which form the isolation system LDRB+LD+SD were modelled in the following manner: the low-damping rubber bearings were modelled using the link type element *Rubber Isolator*, which was put in parallel with a *Gap* element to take into account the different behavior in tension and compression, the lead dampers and the steel dampers, were modeled using the *Plastic (Wen)* element. In Table 1 are given the parameters of the devices which compose the LDRB+LD+SD isolation system, used in the nonlinear time-history analysis.

Table 1 - Parameters of LDRB+LD+SD isolation system used in nonlinear dynamic analysis.

Direction	LDRB		LD				SD			
	Rubber Isolator	*Gap*	*Plastic (Wen)*				*Plastic (Wen)*			
	k_e	k_e	k_e	f_y	k_p/k_e	k	k_e	f_y	k_p/k_e	k
	[kN/m]	[kN/m]	[kN/m]	[kN]	[-]	[-]	[kN/m]	[kN]	[-]	[-]
U1	179400	2511600	15	-	-	-	10	-	-	-
U2	450.5	-	30000	225	0	20	8320	232	0.0173	20
U3	450.5	-	30000	225	0	20	8320	232	0.0173	20
where: k_e is the elastic stiffness; f_y is the yielding strength; k_p is the post-elastic stiffness and k is the yielding exponent.										

Table 2 - Parameters of LRB+LFVD isolation system used in nonlinear dynamic analysis.

Direction	LRB				LFVD		
	Rubber Isolator			*Gap*	*Damper*		
	k_e	f_y	k_p/k_e	k_e	k_e	C	α
	[kN/m]	[kN]	[-]	[kN/m]	[kN/m]	[kNs/m]	[-]
U1	189700	-	-	2655300	243600	304.81	0.4
U2	6530	67.4	0.1	-	-	-	-
U3	6530	67.4	0.1	-	-	-	-
where: k_e is the elastic stiffness; k_p is the post-elastic stiffness; f_y is the yielding strength; C is the damping coefficient and α is the velocity exponent.							

The devices which form the isolation system LRB+LFVD were modeled in the following manner: the lead rubber bearings were modeled using the link type element *Rubber Isolator*, which was put

in parallel with a *Gap* element to take into account the different behavior in tension and in compression and the linear fluid viscous dampers were modeled using the *Damper* element.

In the Table 2 are given the parameters of the devices which compose the LRB+LFVD isolation system, used in the nonlinear time-history analysis.

The seismic action was considered simultaneously in the three directions of the building (two horizontal directions and one vertical direction), complying with the provisions of paragraph 4.5.3.6.2 (4) from the P100-1/2013 seismic code.

The elastic damping was taken into account by using Rayleigh damping, considering the damping ratio of 3% for the vibration modes between $0.5T_1$ and $1.25T_1$ (T_1 is the period of vibration in the fundamental mode).

The response of the isolated building is highlighted for each seismic action described in the Chapter 4 and for each horizontal direction of the building.

The mean relative displacements of the two isolation systems are given in the Fig. 5. The minimum displacements are obtained with the LRB+LFVD isolation system, both on x and y direction. The percentage difference between the two isolation systems, at the level of the isolation plane, is 11.1% for the *x* direction and 11.4% for the *y* direction.
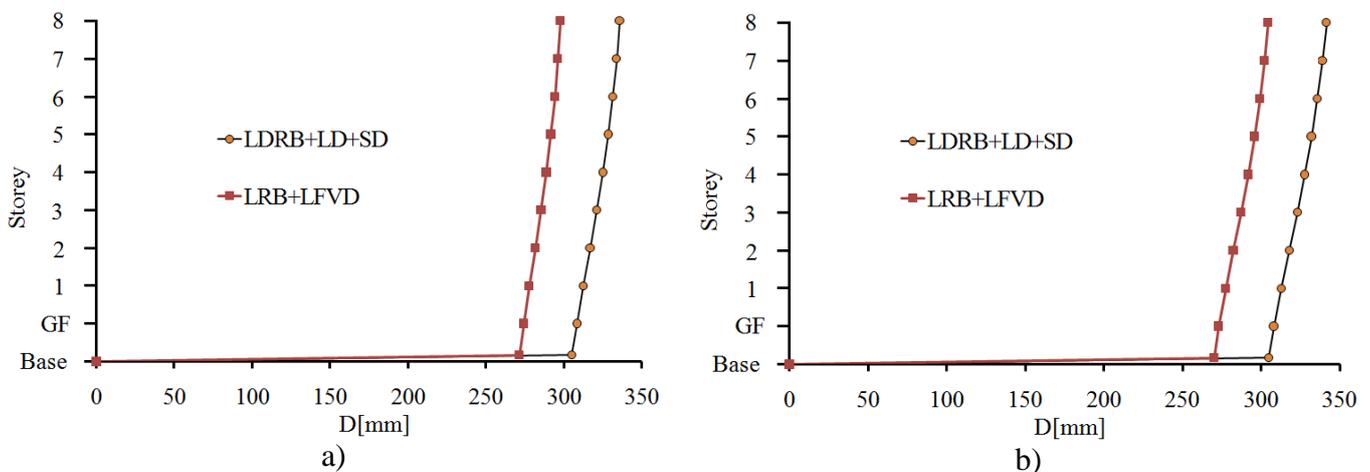
Fig. 5. – The mean relative displacements of the isolated structure, with LDRB+LD+SD system and with LRB+LFVD system: a) *x* direction; b) *y* direction.

In some design situations it is necessary to limit the accelerations in the structure to protect a certain valuable content. Thus, were made comparisons in terms of accelerations both at the level of the isolation plane and at each floor level of the structure. Figure 6 presents the mean absolute accelerations of the two isolation systems. In both horizontal directions of the structure, minimum accelerations are obtained with LRB+LFVD isolation system. The percentage difference between the two isolation systems, at the level of the isolation plane, is 25.5% for the *x* direction of the building and 24.9% for the *y* direction.
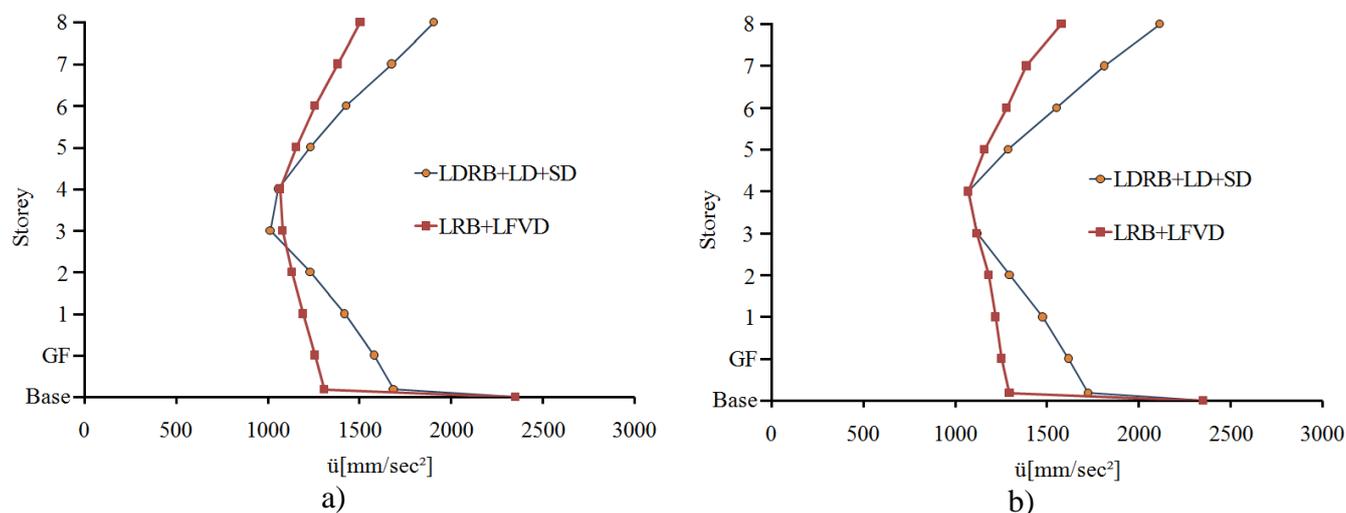
Fig. 6. – The mean absolute accelerations of the isolated structure, with LDRB+LD+SD system and with LRB+LFVD system: a) *x* direction; b) *y* direction.

In the conventional design the energy induced by an earthquake is dissipated through post-elastic deformations of the structural elements. Through base isolation the dynamic properties of the structure are changed, so that the energy induced by an earthquake is greatly diminished and is dissipated, for the most part, by the isolation system.

In the Fig. 7 is presented the mean energy induced by the seismic actions and dissipated through various mechanisms. There ware used the following notations:
   - E_i: the energy induced by the seismic actions;
   - E_{is}: the energy dissipated by the isolation system;
   - E_s: the energy dissipated by the structure through post-elastic deformations and elastic damping;
   - E_k: the kinetic energy;
   - E_p: the potential energy.

In order to have a fair indicator of the energy dissipated by the isolation systems and by the structure, this must be reported to the energy induced by seismic actions. Thus, for the *x* direction of the building, the structure isolated with LDRB+LD+SD system, dissipates 84% of the energy induced by the seismic actions through isolation system and 11.5% through post-elastic deformations and elastic damping. The structure isolated with LRB+LFVD system, dissipates 86.1% of the energy induced by the seismic actions through isolation system and 9.9% through post-elastic deformations and elastic damping.

For the *y* direction of the building, the structure isolated with the LDRB+LD+SD system, dissipates 83.8% of the energy induced by the seismic actions through isolation system and 11.9% through post-elastic deformations and elastic damping. The structure isolated with the LRB+LFVD system, dissipates 85.6% of the energy induced by the seismic actions through isolation system and 10.3% through post-elastic deformations and elastic damping.
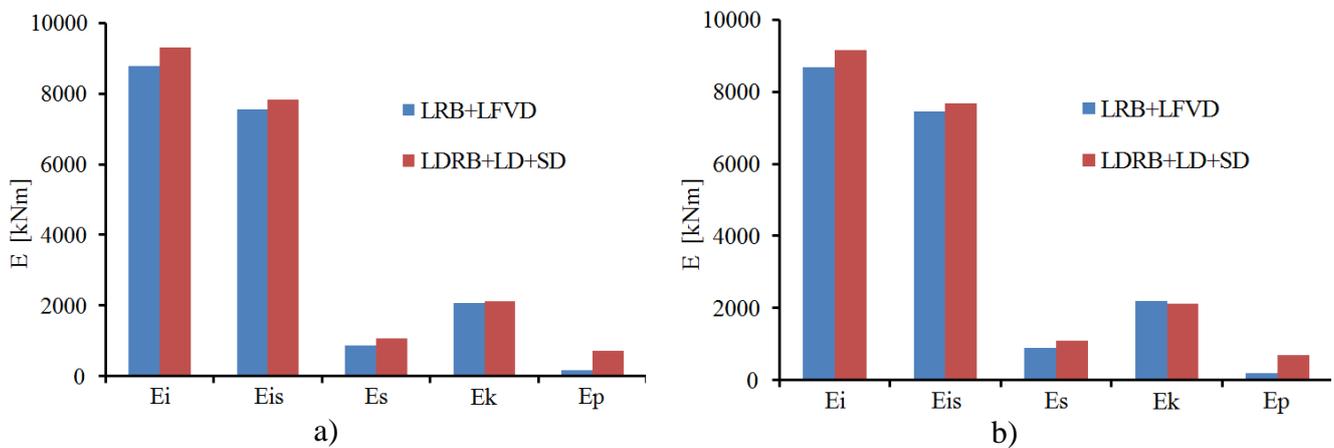
Fig. 7. – The mean energies of the two isolation systems: a) x direction; b) y direction

The base shear force is a key parameter in characterizing the seismic response of structures and is used to design them. In the Fig. 8 is presented the mean base shear forces for the two isolation systems. For both directions of the building, the minimum base shear force is obtained with the LRB+LFVD isolation system. The percentage difference between the two isolation systems is 10.5% for the x direction and 10.6% for the y direction.
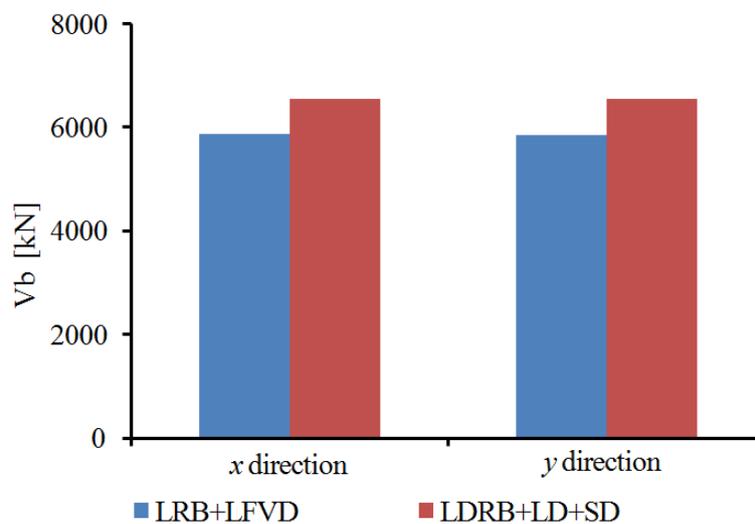
Fig. 8. – The mean base shear forces

6. Conclusions

The performed study examines the seismic performance of two different base isolation systems, considering a vibration period of the isolated structure of 3.5s and a damping ratio of 28%. It was analysed the response in terms of relative displacements, absolute accelerations, dissipated energies and base shear forces of base isolated structure to recorded and generated earthquake ground motions.

The minimum response – in terms of mean relative displacements, mean absolute accelerations, mean dissipated energies and mean base shear forces - is obtained for the structure isolated with LRB+LFVD system. The seismic isolation systems which contains linear fluid viscous dampers gives good results, because they provide the same damping ratio for any value of the lateral displacement and does not introduce stiffness in the isolation system. The hysteretic dampers

increase the stiffness to displacements smaller than the design displacement, so that is decreased the vibration period of the isolated structure. By decreasing the vibration period, there are increased the spectral accelerations. For displacements greater than the design displacement, the hysteretic dampers introduce less damping in the system, so that are increased the spectral accelerations.

Usually, the research from the literature refers to the performances presentation of the various devices which compose the isolation systems and less to study the possible seismic isolation systems. By their composition, the seismic isolation systems have not been studied nor subjected to seismic actions from Vrancea source.

7. References

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