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SEISMIC ISOLATION SYSTEMS FOR BUILDINGS SUBJECTED TO VRANCEA EARTHQUAKES

BY

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Abstract. The efficiency of the base isolation method was demonstrated by the major earthquakes of the late twentieth century and early twenty-first century. However, in Romania, the first seismic isolated building was finished in 2010; thus, no data are available concerning the behaviour of those buildings to Vrancea earthquakes.

The paper presents a comparative study between two seismic isolation systems. The first system is composed of lead rubber bearings and nonlinear fluid viscous dampers and the second system is composed of low-damping rubber bearings and friction dampers.

The study shows that the minimum displacements and minimum base shear forces are obtained with the isolation system composed of low-damping rubber bearings and friction dampers. With the isolation system composed of lead rubber bearings and nonlinear fluid viscous dampers are recorded the minimum accelerations, both at the level of the isolation plane and at each level of the building.

Key words: friction damper; low-damping rubber bearing; nonlinear fluid viscous damper; nonlinear time-history analysis.

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1. Introduction

The seismic isolated buildings subjected to the major earthquakes of the end of the XXth century exhibits a good behaviour without major damages.

In Romania, the first seismic isolated building was Victor Slăvescu building from Bucharest, of which rehabilitation was completed in 2010. Thus, no data are available concerning the behaviour of seismic isolated buildings to the earthquakes from Vrancea source.

This study makes a comparison between two different seismic isolation systems. The first system is composed of lead rubber bearings and nonlinear fluid viscous dampers (LRB+NFVD) and the second system is composed of low-damping rubber bearings and friction dampers (LDRB+FD). The isolation systems were used to isolate a reinforced concrete building having the height regime of ground floor and eight storeys.

The comparison terms ware: relative displacements, absolute accelerations, base shear forces and dissipated energies, considering the seismic action from Vrancea source.

2. Description of the Building and of the Seismic Isolation Systems

The analysed structure is a dual structure, with reinforced concrete shear walls and frames, for which was considered the Bucharest location.

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

The resistance to the lateral forces is provided by the reinforced concrete shear walls, placed on both directions of the building and reinforced concrete frames. The wall thickness on the *x*-direction is 35 cm and on the *y* direction is 30 cm, being constant on the entire height of the building. The columns are made of square section of 70 cm × 70 cm, without reduction of section with height. The longitudinal beams are made of T cross-section with the web thickness of 35 cm, the height of 70 cm, the flange thickness of 16 cm and flange width of 100 cm. The transversal beams are also made of T cross-section with the web thickness of 30 cm, the height of 60 cm, the flange thickness of 16 cm and flange width of 100 cm. The thickness of the reinforced concrete slabs was taken 16 cm.

At the level of the isolation plane it was considered a reinforced concrete slab of 16 cm thickness, having the main role of distributing the horizontal forces to the isolation system.

The reinforced concrete slab is supported on the longitudinal and on the transversal beams of T cross-section with the web thickness of 100 cm, the height of 60 cm, the flange thickness of 16 cm and the flange width of 170 cm.

These beams have greater cross-sections to avoid plastic hinges occurrence and to ensure a good connection with the isolation devices.

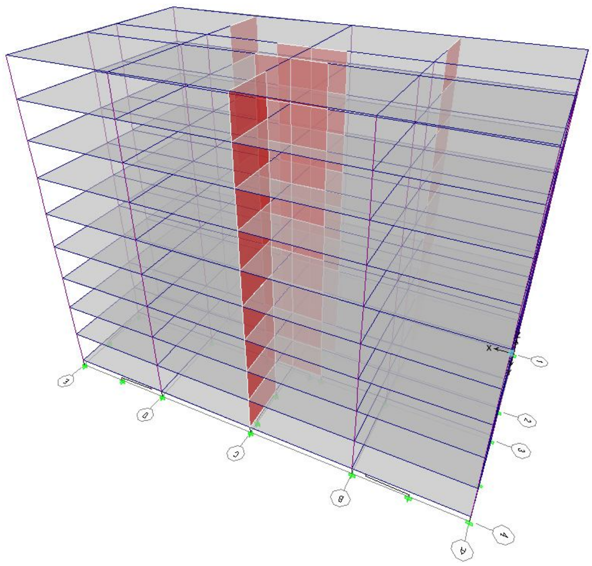


Fig. 1 – General view of the analysed building.

The analysed building was seismically isolated, using two different seismic isolation systems. The first system (LRB+NFVD) is composed of twenty five lead rubber bearings (one bearing under each column and two bearings under each reinforced concrete shear wall) and twelve nonlinear fluid viscous dampers (six on the longitudinal direction and six on the transversal direction of the building).

The second system (LDRB+FD) is composed of twenty five low-damping rubber bearings (one bearing under each column and two bearings under each reinforced concrete shear wall) and friction dampers (six on the longitudinal direction and six on the transversal direction of the building).

3. Preliminary Design and Structural Analysis of the Isolated Structure

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} = 3.5 s, 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.

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

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

The effective horizontal stiffness, k_{ef}^{lrb}, of one lead rubber bearing was determined using eq.

$$k_{\text{ef}}^{lrb} = \left(\frac{2\pi}{T_{is}}\right)^2 \frac{G_{SC}}{n_{hdrb}g} = \left(\frac{2\pi}{3.5\ \text{s}}\right)^2 \frac{65{,}668.16kN}{25\times 9.81\ \text{m/s}^2} = 862.9\,\text{kN/m}, \quad (2)$$

where: G_{SC} is the total weight of the building in the special combination of loads; n_{hdrb} – the number of high damping rubber bearings and g – the ground acceleration.

The damping constant, C_{nvd}, of the nonlinear fluid viscous dampers was determined using eq.

$$C_{nvd} = \frac{2\pi G_{SC}\xi_{nvd}}{n_{nvd}\left(\frac{2\pi}{T_{is}}\right)^{\alpha-2} d_{dc}\lambda g} = \frac{2\pi 65{,}668.16\ \text{kN}\times 13\%}{6\left(\frac{2\pi}{3.5s}\right)^{0.4-2} 0.289m\times 3.62\times 9.81\text{m/s}^2} = 304.8\ \text{kN}\frac{s^{0.4}}{m^{0.4}}, \quad (3)$$

where: ξ_{nvd} is the damping ratio of the nonlinear fluid viscous dampers; n_{nvd} – the number of the nonlinear fluid viscous dampers on x- and y-direction, respectively and λ – the coefficient of the nonlinear fluid viscous dampers.

The effective stiffness, k_{ef}^{fd}, of one friction damper was determined using eq.

$$F_f^{fd} = \mu_f N_{fd} = 0.6\times 760\ \text{kN} = 456\ \text{kN},$$
$$k_{\text{ef}}^{fd} = \frac{F_f^{fd}}{d_{dc}} = \frac{456\ \text{kN}}{0.289\ \text{m}} = 1{,}577.9\ \text{kN/m}, \quad (4)$$

where: F_f^{fd} is the friction force produced by one friction damper; μ_f – the friction coefficient and N_{fd} – the tightening force of friction dampers.

The effective horizontal stiffness, k_{ef}^{ldrb}, of one low-damping rubber bearing was determined using eq.

$$k_{\text{ef}\_s}^{ldrb} = \left(\frac{2\pi}{T_{is}}\right)^2 \frac{G_{SC}}{g} - n_{fd} k_{\text{ef}}^{fd} = \left(\frac{2\pi}{3.5s}\right)^2 \frac{65668.16 \text{ kN}}{9.81 \text{ m/s}^2} - 6\times 1{,}577.9 \text{ kN/m} = \\ = 12{,}105.8 \text{ kN/m}, \\ k_{\text{ef}}^{ldrb} = \frac{k_{\text{ef}\_s}^{ldrb}}{n_{ldrb}} = \frac{12105.8 \text{ kN/m}}{25} = 484.3 \text{ kN/m}, \tag{5}$$

where: $k_{\text{ef}\_s}^{ldrb}$ is the effective horizontal stiffness of the all low-damping rubber bearings; n_{fd} – the number of friction dampers on longitudinal direction of the building or on the transversal direction of the building and n_{ldrb} – the number of the low-damping rubber bearings.

The linear static analysis was performed using the ETABS v9.2.0 computer program, considering the stiffness of the elements reduced with fifty percent due to the concrete cracking.

Modelling of the lead rubber bearings was made using the link type element *Isolator 1*, which was put in parallel with a *Gap* element to take into account the different behaviour in tension and in compression. For the nonlinear fluid viscous damper was used a *Damper* element.

Modelling of the low-damping rubber bearings was made using the link type element *Linear*, which was put in parallel with a *Gap* element to take into account the different behaviour in tension and in compression. The friction damper was modelled using the link type element *Plastic 1*.

The horizontal seismic forces, f_i, applied to the each level of the analysed structure, were determined using eq.

$$f_i = m_i S_a\left(T_{\text{ef}}, \xi_{\text{ef}}\right) = m_i \frac{S_e\left(T_{\text{ef}}, \xi_{\text{ef}}\right)}{q}, \tag{6}$$

where: m_i is the mass of each storey; $S_a(T_{\text{ef}},\xi_{\text{ef}})$ – the design spectral acceleration corresponding to the effective period of vibration, T_{ef}, in the fundamental mode of vibration of the analysed structure, and to the effective damping, ξ_{ef}; $S_e(T_{\text{ef}}, \xi_{\text{ef}})$ – the elastic spectral acceleration corresponding to the effective period of vibration, T_{ef}, in the fundamental mode of vibration of the analysed structure, and to the effective damping, ξ_{ef}; q – the behaviour factor taken as 1.5.

The structural elements were designed like low-dissipative elements, adopting the ductility class L, according to SR EN 1998-1:2004. According to the recommendations of SR EN 1998-1:2004 and P100-1/2006, it is not necessary to meet the requirements of the capacity method and global or local ductility. The reinforcement steel used for the longitudinal bars was S355 and for the stirrups was S235. The concrete class used was C20/25.

4. The Seismic Action

The seismic action is described by six artificial accelerograms compatible with the design spectrum for Bucharest and one accelerogram, recorded on INCERC-Bucharest site, corresponding to the N-S component of the March 4, 1977 earthquake.

The recorded accelerogram was scaled, according to the P100-1/2006 seismic code, to the maximum ground acceleration of 0.24 g, 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 computer program using two procedures. Three accelerograms were generated starting from the recorded accelerograms, on the INCERC-Bucharest site, of the March 4, 1977; August 30, 1986 and May 30, 1990 earthquakes, N-S component. The frequency content of the three recorded accelerograms was adjusted, using Fourier transformation method, to fit the target spectrum (design spectrum from the P100-1/2006 seismic code, corresponding to Bucharest city). The maximum ground acceleration was considered 0.24 g.

The other three accelerograms were generated using random processes by correction in frequency domain. It were applied Saragoni & Hart, Compound and Exponential envelope shapes.

5. Nonlinear Time-History Analysis and Comparative Results

The nonlinear dynamic analysis of the isolated structure was performed using the SAP2000 v15.1.0 computer program, considering the structural elements and the isolation systems with nonlinear behavior.

The nonlinear behavior of beams and columns was modeled with plastic hinges at the elements ends (concentrated plasticity model) of *M3* type and of *PM2M3* type, respectively.

The shear walls were modeled with *shell layered-nonlinear* elements, with nonlinear behavior in both bending with axial force and shear force. For the concrete from the boundary elements of the shear wall was used a model with constant confinement (Mander model, 1988) and for the reinforcement was used the model automatically generated by the program with yielding plateau and post-elastic hardening.

The strengths of the materials were considered with mean values.

The devices which form the isolation system LRB+NFVD 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 nonlinear fluid viscous dampers were modeled using the *Damper* element.

In the Table 1 are given the parameters of the devices which compose the LRB+NFVD isolation system, used in the nonlinear time-history analysis.

Table 1
Parameters of LRB+NFVD Isolation System Used in Nonlinear Dynamic Analysis

Direction	*Rubber Isolator*			*Gap*	*Damper*		
	k_e kN/m	f_y kN	k_p/k_e	k_e kN/m	k_e kN/m	C kN.s/m	α
U1	189,700	–	–	2,655,300	243,600	304.81	0.4
U2	6,530	67.4	0.1	–	–	–	–
U3	6,530	67.4	0.1	–	–	–	–

k_e is the elastic stiffness; k_p – the post-elastic stiffness; f_y – the yielding strength; C – the damping coefficient and α – the velocity exponent.

The devices which form the isolation system LDRB+FD were modeled in the following manner: the low-damping 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 compression and the friction dampers were modeled using the *Plastic (Wen)* element.

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

Table 2
Parameters of the LDRB+FD Isolation System Used in the Nonlinear Dynamic Analysis

Direction	*Rubber Isolator*	*Gap*	*Plastic (Wen)*			
	k_e kN/m	k_e kN/m	k_e kN/m	f_y kN	k_p/k_e	k
U1	179,800	2,517,200	456,000	456	0	20
U2	484.3	–	–	–	–	–
U3	484.3	–	–	–	–	–

k_e is the elastic stiffness; f_y – the yielding strength; k_p – the post-elastic stiffness and k –the yielding exponent.

The seismic action was considered simultaneously in the three directions of the building, respecting the provisions of paragraph 4.5.3.6.2 (4) from P100-1/2006 seismic code.

The elastic damping was taken into account by using Rayleigh damping, considering the damping ratio of 3% for the vibration modes between $0.2T_1$ and $1.5T_1$ (T_1 is the period of vibration in the fundamental mode).

The response of the isolated structure is highlighted for each seismic action described in the § **4** and for each horizontal direction of the structure.

The mean relative displacements of the two isolation systems are given in the Fig. 2. For the *x*-direction of the building, the two isolation systems experience almost the same displacements. For the *y*-direction of the building, the minimum displacements are obtained with the LDRB+FD isolation system. The percentage difference between the two isolation systems, at the level of the isolation plane, is 1.5% for the *x*-direction and 7.8% for the *y*-direction.

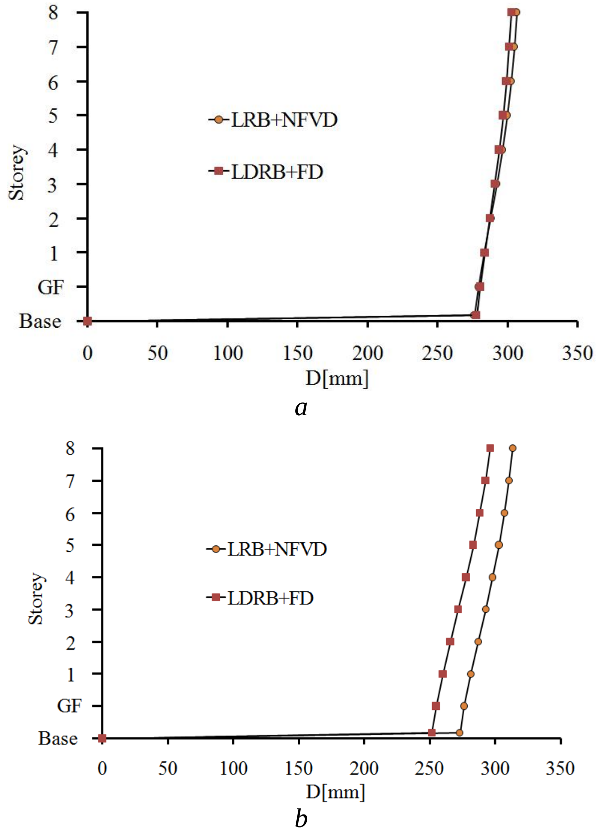


Fig. 2 – The mean relative displacements of the isolated structure, with LRB+NFVD and LDRB+FD system: *a* – *x*-direction; *b* – *y*-direction.

In same design cases 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. Fig. 3 presents the mean absolute accelerations of the two isolation systems**.** In both horizontal directions of the structure, minimum accelerations are obtained with LRB+NFVD isolation system. The percentage difference between the two isolation systems, at the level of the isolation plane, is 45.5% for the *x*-direction of the building and 44.4% for the *y*-direction.

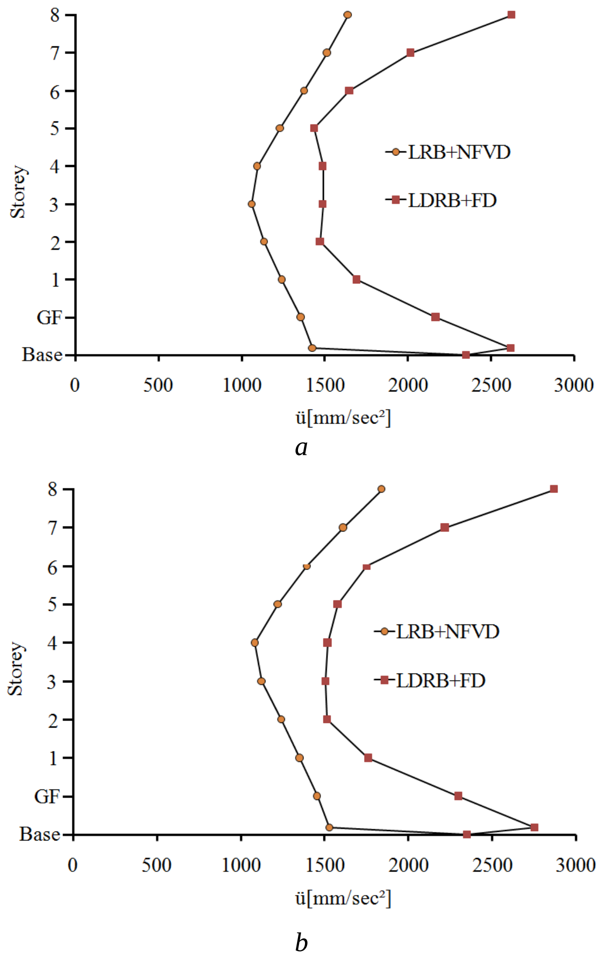
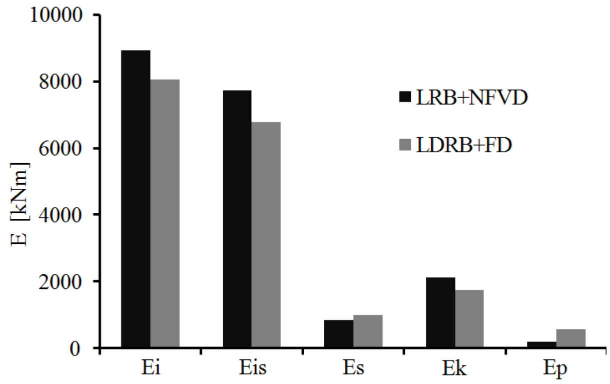


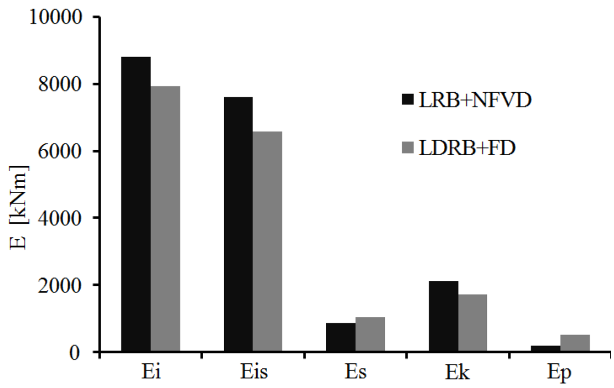
Fig. 3 – The mean absolute accelerations of the isolated structure, with LRB+NFVD and LDRB+FD system: *a* – *x*-direction; *b* – *y*-direction.

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. To analyse the energy dissipated by the two isolation systems, the hysteretic curves was integrated through the entire duration of the seismic actions described in the § **4**.

In the Fig. 4 is presented the mean energy induced by the seismic actions and dissipated through various mechanisms. There were 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.



a



b

Fig. 4 – The mean energies of the two isolation system:
a – *x*-direction; *b* – *y*-direction.

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 LRB+NFVD system, dissipates 86.6% of the energy induced by the seismic actions through isolation system and 9.6% through post-elastic deformations and elastic damping. The structure isolated with LDRB+FD system, dissipates 83.9% of the energy induced by the seismic actions through isolation system and 12.3% through post-elastic deformations and elastic damping.

For the *y*-direction of the building, the structure isolated with the LRB+NFVD system, dissipates 86.2% of the energy induced by the seismic actions through isolation system and 10% through post-elastic deformations and elastic damping. The structure isolated with the LDRB+FD system, dissipates 82.9% of the energy induced by the seismic actions through isolation system and 13.3% through post-elastic deformations and elastic damping.

The base shear force is a key parameter in characterizing the seismic response of structures and is used to design them. In the Fig. 5 is presented the mean base shear forces for the two isolation systems. For the *x* direction of the building, the two isolation systems have almost the same base shear force. For the *y* direction of the building, the minimum base shear force is obtained with the LDRB+FD isolation system. The percentage difference between the two isolation systems is 0.8% for the *x*-direction and 8.8% for the *y*-direction.

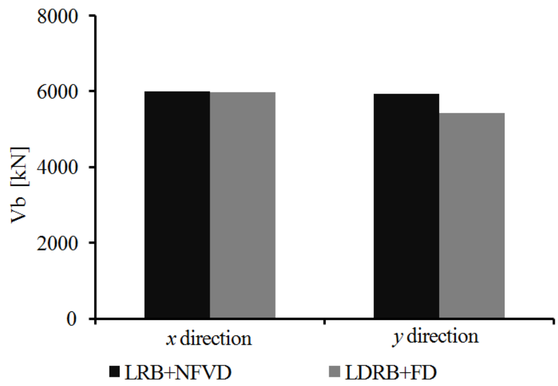


Fig. 5 – The mean base shear forces.

6. Conclusions

The performed study examines the seismic performance of two different isolation systems, considering a vibration period of the isolated structure of 3.5 s and a damping ratio of 28%. It was analysed the response in displacements, accelerations, dissipated energy and base shear forces of the structure and isolation systems to the seismic actions from Vrancea source.

The minimum displacements and minimum base shear forces are obtained with the LDRB+FD isolation system. With the LRB+NFVD isolation system are recorded the minimum accelerations, both at the level of the isolation plane and at each level of the building. The LRB+NFVD isolation system dissipates more energy than the LDRB+FD isolation system.

Both isolation systems have advantages and disadvantages. Depending on the design requirements, it can be used a system or another; for example, if it is required the limitation of the storey accelerations, the LRB+NFVD isolation system is more suitable. The major disadvantage of the LDRB+FD isolation is that it does not possess recentering capacity. To return to the initial position, it is required an additional recentering system.

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SISTEME DE IZOLARE SEISMICĂ PENTRU CLĂDIRI SUPUSE LA CUTREMURE VRÂNCENE

(Rezumat)

Eficienţa metodei de izolare a bazei a fost demonstrată de cutremurele majore de la sfârşitul secolului XX şi începutul secolului XXI. Totuşi, în România, prima clădire izolată seismic a fost finalizată în anul 2010; astfel încât nu există date referitoare la comportarea acestor clădiri la cutremurele din sursa Vrancea.

Se prezintă rezultatele unui studiu comparativ între două sisteme de izolare seismică. Primul sistem este compus din izolatori elastomerici cu miez de plumb şi amortizori cu fluid vâscos neliniari, iar al doilea sistem este compus din izolatori elastomerici cu amortizare mică şi amortizori cu frecare.

Studiul a arătat că deplasările minime și forțele tăietoare de bază minime sunt obținute cu sistemul de izolare compus din izolatori elastomerici cu amortizare mică şi amortizori cu frecare. Cu sistemul de izolare format din izolatori elastomerici cu miez de plumb şi amortizori cu fluid vâscos neliniari sunt înregistrate accelerațiile minime, atât la nivelul planului de izolare cât şi la nivelul fiecărui etaj al construcției.