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SEISMIC STRENGHTENING OF EXISTING REINFORCED CONCRETE FRAMES USING PASSIVE ENERGY SYSTEMS

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Abstract. *In Romania there are many reinforced concrete (RC) buildings designed to resist according to out-of-date technical code only for vertical loads. The severe damages and human losses caused by the Romanian Vrancea earthquake in 1977, show the need for developing efficient methods for the seismic strenghtening of existing under-designed reinforced concrete (RC) structures. This paper presents seismic retrofitting of the existing reinforced concrete (RC) frames using 2 passive energy-dissipating devices: metallic dampers (displacement-dependent) and viscous dampers (velocity-dependent), to enhance the performance of seismically vulnerable reinforced concrete (RC) buildings. The retrofitting system is installed within the bays of an RC building frame to enhance the stiffness, strength and ductility of the structure. Fluid viscous dampers dissipate energy by transforming it into heat, forcing a fluid with high viscosity through an orifice, in order to reduce simultaneously displacements and forces. Metallic dampers are some of the most efficient energy dissipation devices, using the inelastic deformation of metal. As the steel plates deform, they provide displacement dependent stiffness and energy dissipation. Both of these devices have stable hysteretic curves and resist to a high number of loading – unloading cycle. Nonlinear time history analyses of the reinforced concrete frame with and without strengthening conducted in order to reveal and the improved seismic response in terms of roof maximum displacements, drifts and base shear forces. The strengthened models will exhibit enhanced lateral strength, stiffness ductility as compared to the RC moment resisting frame.*

1 INTRODUCTION

Earthquake design spectra from the seismic code P13-70 [1] in 1970 was according to the Californian shallow-focus earthquake, unlike the Romanian Vrancea intra-focus Earthquake. In Figure 1 we can see a comparison between spectral curves for Bucharest city area, according to the seismic code P13/70 and the current seismic Romanian prescriptions P100-1/2006 [2]. According to P100-1-2006 [3], seismic parametres for Bucharest city area are: design ground acceleration 0.24g, with the upper limit of the period of the constant spectral acceleration branch Tc = 1.6s (for a seismic action with the mean return period of 100 years - Ultimate Limit State). The maximum dynamic amplification factor of horizontal ground acceleration of the structure is, according to P100-1-2006 code, β_0=2.75.

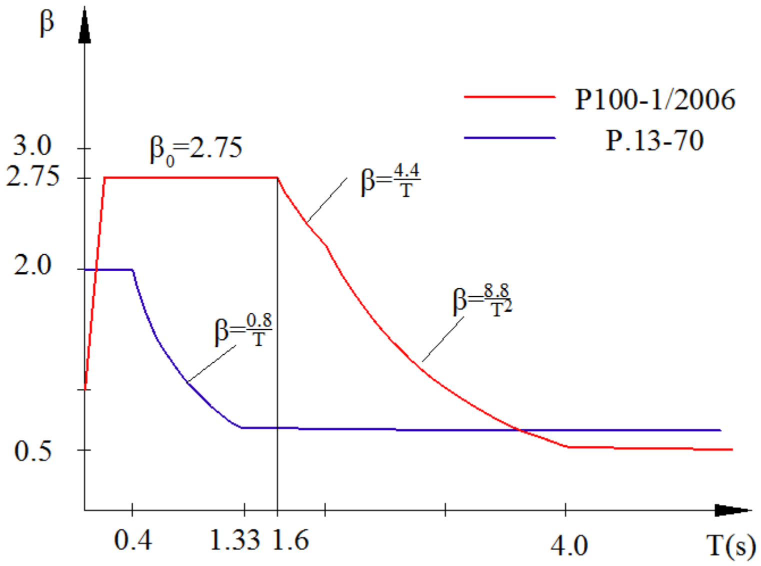


Figure 1: Evolution for the spectral curves in romanian seismic codes.

In Figure 1 we can observe the evolution of the dynamic factor β for Bucharest city by comparing the spectral curve according to P13/70 with the one according to P100-1:2006 (where T is the fundamental period of the structural system and T_B, T_C, T_D - are corner periods) :

For P.13-70:

$$0.6 \leq \beta = \frac{0.8}{T} \leq 2.0 \tag{1)[1}$$

For P100-1/2006:

$$\begin{gathered} 0 \leq T \leq T_B \text{ - } \beta(T) = 1 + \frac{(\beta_0 - 1)}{T_B} T \\ T_B \leq T \leq T_C \text{ - } \beta(T) = \beta_0 \\ T_C \leq T \leq T_D \text{ - } \beta(T) = \beta_0 \frac{T_C}{T} \\ T > T_D \text{ - } \beta(T) = \beta_0 \frac{T_C \cdot T_D}{T^2} \end{gathered} \tag{2)[2}$$

Further than that, the seismic code in 1970 didn't contain requirements regarding stiffness and ductility for structures. Reinforced concrete frames (RCF) designed in accordance with P.13-70 are characterized by deficiencies resulting from inadequate design requirements: poor bending and shear capacity for structural elements (beams and columns), improper stiffness and ductility. For economically considerations and life safety, these buildings have undergone strengthening in order to improve lateral stiffness, strength and ductility.

This paper proposes to improve the seismic behaviour of a vulnerably RC framed structure designed in accordance with the *"Standard for design of civil and industrial buildings in seismic regions" P.13 – 70* , by using two modern retrofitting methods: metallic dampers (displacement dependent) and viscous dampers (velocity dependent).

All the analyses are computed using SAP2000 software [4].

2 DESCRIPTION OF EXISTING BUILDING

2.1 Description of Existing Building

In purpose of this work, a 8 stories RC framed structure was considered, located in Bucharest city, Romania. The building has two spans of 6.00m, 6 bays of 4.00m and 8 stories of 3.20m, as we can see in Figure 1 a,b. The sectional properties of elements for the are taken as follows: columns for 1-4 stories- 35x70cm; columns for 5-8 stories-35x40cm; transverse beams (x direction) – 30x55cm; longitudinal beams (y direction): 30x45cm; thickness of RC slab = 10 cm. The cross-sections for the RC structural elements and the reinforcement used are presented in Figure 1c. Elastic stiffness for RC elements (beams and columns) was considered with the effect of cracked sections, equal to half of the non-cracked sections.

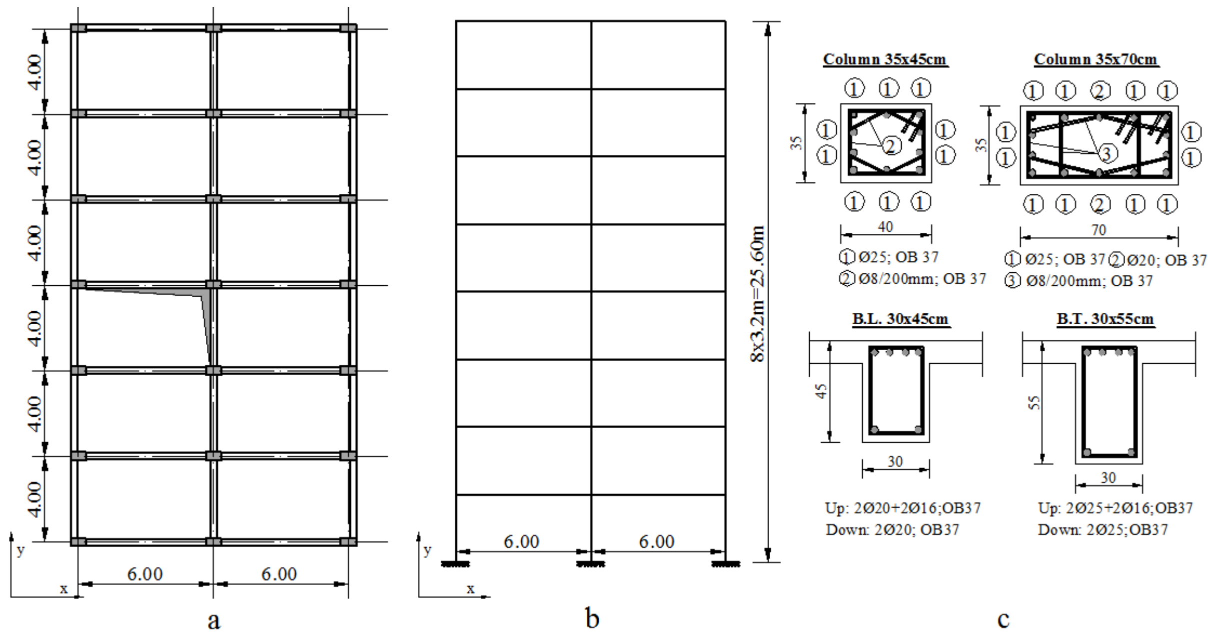


Figure 2: Structural systems: a) Plan view; b) Elevation view; c) Cross sections for structural elements.

For transverse and longitudinal reinforcement of all structural cross-sections was used OB37 steel (yield stress - $f_y = 235\ MPa$, ultimate strength $f_t = 360\ MPa$) and the concrete class for all structural elements is C12/16 ($f_{cm} = 20\ MPa$).

Self loads are considered automatically by SAP2000 and the loads are taken in accordance with EN Eurocodes: permanent loads (PL) – 3.50 kN/m^2, live loads (LL) – 3.00 kN/m^2, snow (S) - 2.00 kN/m^2.

2.2 Seismic Evaluation for Existing Structure

Evaluation for the existing structure is made in terms of strength, stiffness and ductility requirements.

Using SAP2000 software, the following analyzes were performed: static linear-static forces equivalent application under P100/1-2006 on the x and y direction, modal analysis and nonlinear static analysis with triangular lateral force distribution for both incremental direction: transversal (x) and longitudinal (y).

In Table 1 we can see the modal analysis results: time periods and modal participation mass ratios for the first three modes of vibration.

Mode of vibration	Period T (s)	Modal participation mass ratios		
		UX	UY	RZ
1	1.77	0	0.81	0
2	1.50	0.75	0	0
3	1.39	0.002	0.0005	0.18

Table 1. Time period and modal participation mass for first three modes of vibration.

Analyzing Table 1 we can conclude that the fundamental mode of vibration is translation in the weak longitudinal direction, with a time period of 1.77s, and the second mode is translation in the X transverse direction, with a time period of 1.50s.

Equivalent static seismic forces were applied according P100-1-2006, using prescription for Bucharest city area presented in Chapter 1.

Regarding **strength requirements**, structural elements have poor bending and shear capacity, because the structure has been dimensioned according to out-of-date technical codes.

The **stiffness requirements** are verified in accordance with Annex E of P100-1-2006. For Serviceability Limit State (SLS) inelastic drift don't exceed the drift limit of 0.16m, but for Ultimate Limit State (ULS), inelastic drifts exceed drift limit for ULS – 0.08m, as we can see in Figure 6.

Ductility requirements are verified using static nonlinear pushover analysis.

The nonlinear behaviour of structural members was modeled using plastic hinges and acceptance criteria according to FEMA 356: hinges for columns are due to axial force-bending moment interaction, hinges for beams are due to bending moment.

The target displacements and the biliniarization for push-over curves on both direction have been made according to Annex B in SR EN 1998-1:2004 [5], as it is shown in Figure 2.

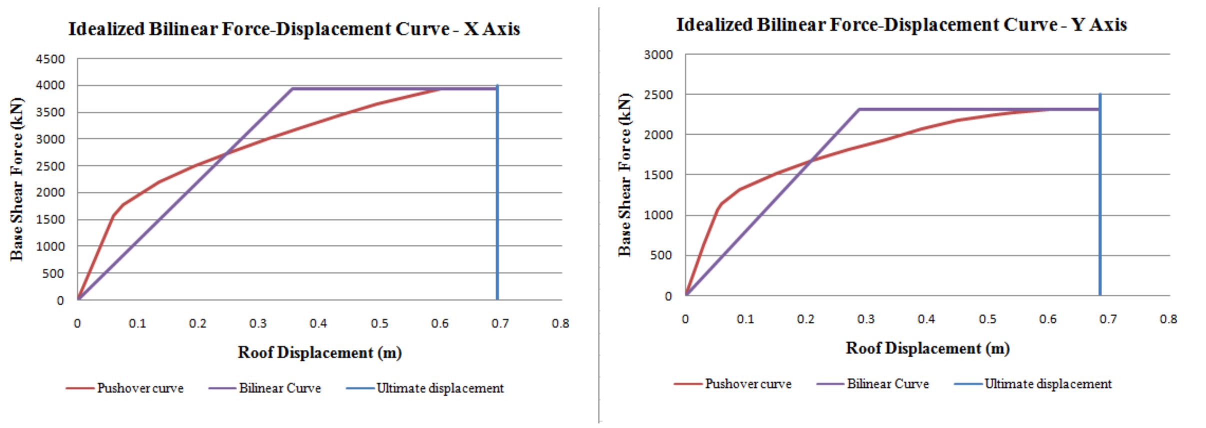


Figure 3: Structural systems – elevation view: a) CBF; b) EBF; c) VDS

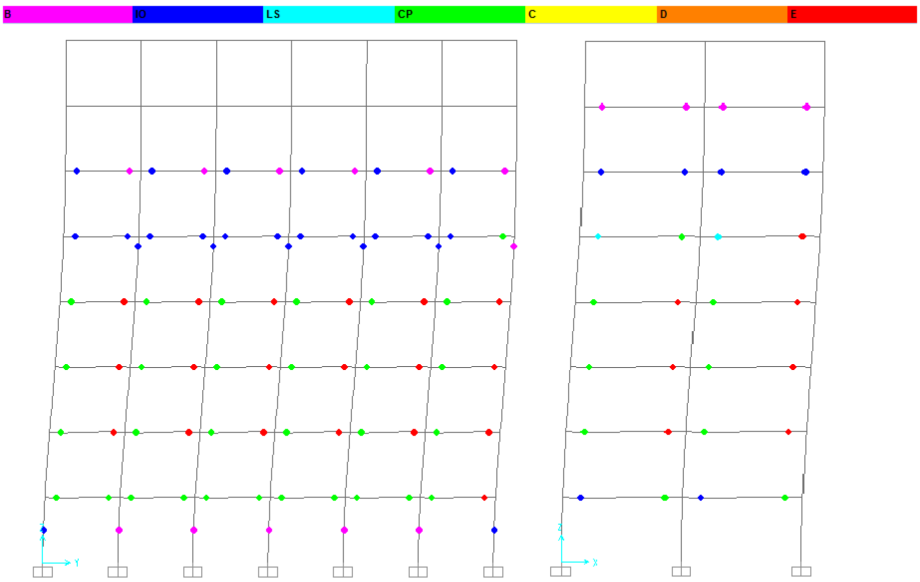


Figure 4: Plastic hinges plot for longitudinal and transverse direction.

The plastic hinges plotted for the last step of push-over analyses (target displacement) in Figure 4, provide information about local and global failure mechanism in the structure. One can observe that the global plastic behaviour of the structure provides a weak column–strong beam response, but several beams from the first levels locally fail.

2.3 Conclusions

Analyses results on the considered under-designed RC structure reveal that the building doesn't meet strength, stiffness and ductility requirements for ensuring life safety. The paper recommends seismic strengthening using efficient methods.

3 SEISMIC STRENGTHENING FOR RC FRAMED STRUCTURE

3.1 Description of the Retrofitting Methods

To enhance the performance of seismically vulnerable reinforced concrete (RC) building, we will consider 2 retrofitting systems using passive energy-dissipating devices: metallic dampers retrofitting system (MDRS) – Figure 5.a,c, and viscous dampers retrofitting system (VDRS) – Figure 5.b,c.

To avoid large concentrations of axial efforts in RC beams transmitted by the passive dampers, steel collector beam has been inserted at the interface of reinforced concrete frame beam with damper, connected to the existing concrete with bolts and epoxy mortar. Metal beam that ensures the bending of concrete elements over a larger surface area eliminate the concentrations of efforts and thus to increase the strength of the existing framework. Diagonals are attached directly to the existing concrete through metal plates, the bolts and epoxy grout.

Columns for the first two levels have been retrofitted using steel jackets.

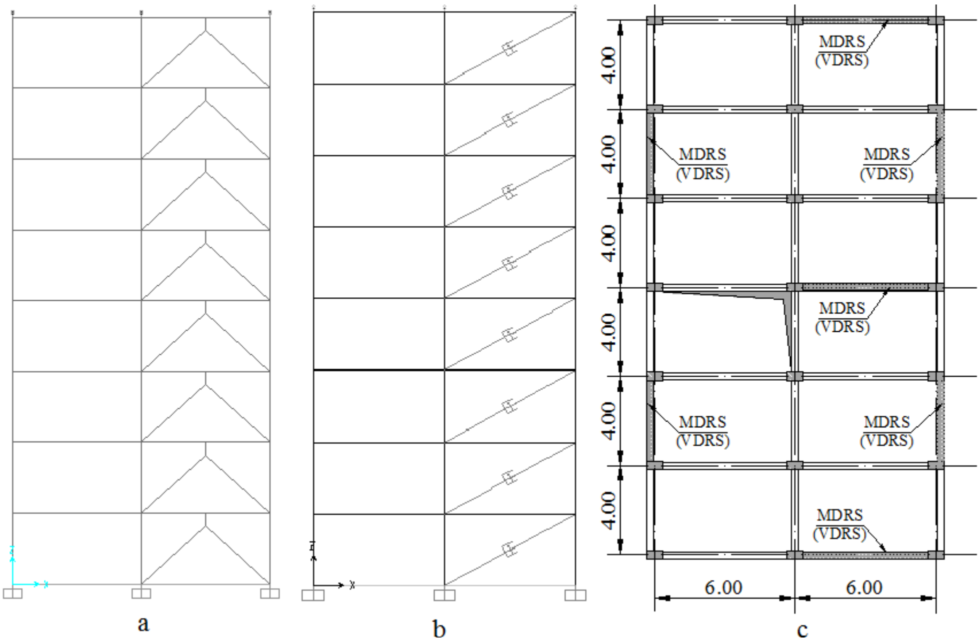


Figure 5: a. Elevation view for MDRS; b. Elevation view for VDRS; c. Placement of dampers.

Forces in metalllic dampers are proportional to displacements. In these systems, most part of the seismic energy is disipated through yielding of metallic elements specially designed to deform in inelastic range. This approach is assimilated in eccentrically braced frames (EBF) with vertical removable short links, that are separated from the main structure, and act as structural fuses that can be replaced after strong earthquake disturbances. Short links withstand large inelastic deformations and dissipate a great amount of energy, remaining effective for many cycling loads. [6]

Forces in viscous dampers are proportional to the velocity of the mass. Fluid viscous dampers work on the principle of fluid flow through orifices. They are composed of a stainless steel piston that moves inside a close cylinder containing a viscous fluid, and connected to an element with orifices at one end. The difference pressure forces the fluid to flow through the orifices and the seismic energy is converted into heat which is released into atmosphere. [7]

The damper force depends on the relative velocity between the two ends of the damper and can be expressed using Eq.(2)[7]:

$$F_{disip} = c \times \nu^{\alpha} \tag{2)[7}$$

where: F_{disip} – is the damper force; c – is the damping constant for the device; ν - is the relative velocity between the two ends of device and α is the velocity exponent (damping exponent) for the device.

To determine viscous dampers characteristics, the methodology described in FEMA 356 is used. The damping constant *c* of viscous dampers will be calculated from the condition for the equivalent damping ratio (ξ_{eq}), due to the action of the supplemental viscous dampers, to be equal with 25% of the critical damping ratio.

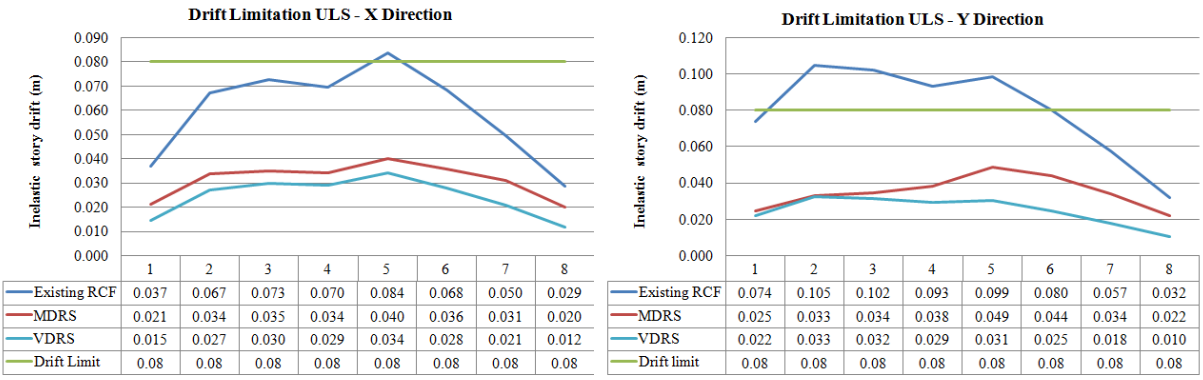
The base shear force of the structure is affected by the factor η described in Eq. (3)[7] corresponding to the equivalent damping ratio (ξ_{eq25}=25%).

$$\boldsymbol{\eta} = \sqrt{\frac{\mathbf{10}}{\mathbf{5}+\boldsymbol{\xi}_{\boldsymbol{eq25}}}} = \mathbf{0.57} \tag{3)[7}$$

The resulted values for the damping constants of devices is: c_x=9100 kNs/m (X direction) and c_y=6500 kNs/m (Y direction).

3.2 Drift Limitation

Inelastic story drifts and drift limit for Ultimate Limit State (ULS) computed in accordance with Romanian Seismic Code P100-1/2006 are presented in Figure 6 to compare the seismic response for existing RC frames with the two retrofitted structures.



X Direction:

	1	2	3	4	5	6	7	8
Existing RCF	0.037	0.067	0.073	0.070	0.084	0.068	0.050	0.029
MDRS	0.021	0.034	0.035	0.034	0.040	0.036	0.031	0.020
VDRS	0.015	0.027	0.030	0.029	0.034	0.028	0.021	0.012
Drift Limit	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08

Y Direction:

	1	2	3	4	5	6	7	8
Existing RCF	0.074	0.105	0.102	0.093	0.099	0.080	0.057	0.032
MDRS	0.025	0.033	0.034	0.038	0.049	0.044	0.034	0.022
VDRS	0.022	0.033	0.032	0.029	0.031	0.025	0.018	0.010
Drift limit	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08

Figure 6: Comparative inelastic ULS drifts and drift limitation.

The retrofitting systems provide the required stiffness to existing structure, so lateral drifts for ULS are reduced by up to 52% using MDRS and up to 60% using VDRS. Both new structural systems meet the stiffness requirements.

3.3 Dynamic nonlinear analysis results

Dynamic analysis using the time history (TH) method reveals strengthened RC frames response, in terms of roof displacements, roof accelerations (node 267 - top level of a perimeter frame) and base shear force, at discrete time steps. The earthquake record considered in this work is the North-South component of March 4th, Vrancea (Romania) 1977 accelerogram, recorded at INCERC, Bucharest, scaled by a factor of 1.2 corresponding to a mean return period of 100 years.

The nonlinear behaviour of steel braces and short dissipative links was modeled using plastic hinges and acceptance criteria according to FEMA 356: hinges for braces are due to axial force, hinges for short links are due to shear force.

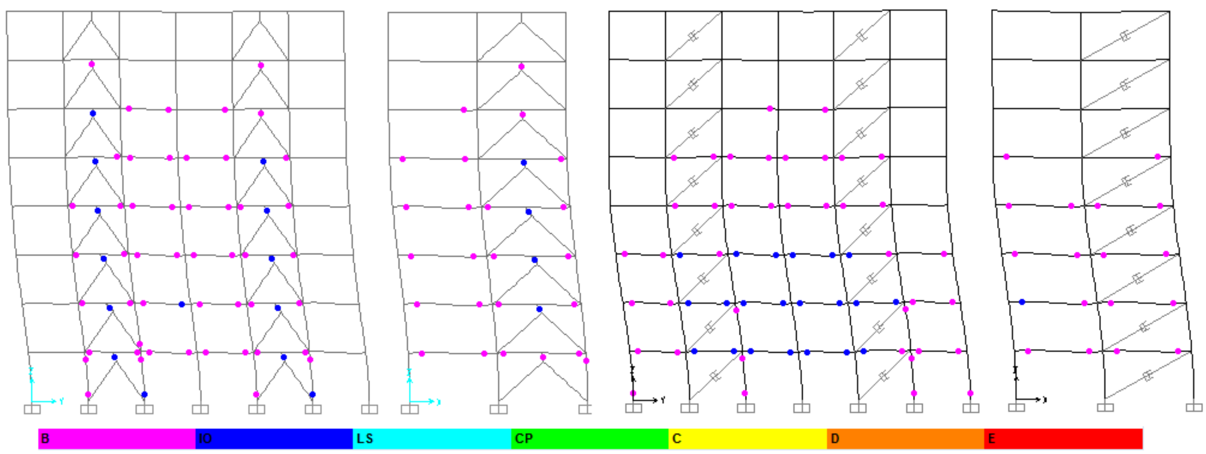


Figure 7: Plastic hinges plot for the two retrofitted systems in the last TH step

Plastic hinges plot for the two retrofitted systems in the last TH step in Figure 7 reveal the improved ductility for the RC structure. When subjected to TH analysis, the existing structure collapsed. Figure 7 indicates the much improved responses for the RC considered structure, plastic hinges in structural RC elements don't exceed Immediate Occupancy (IO) limit.

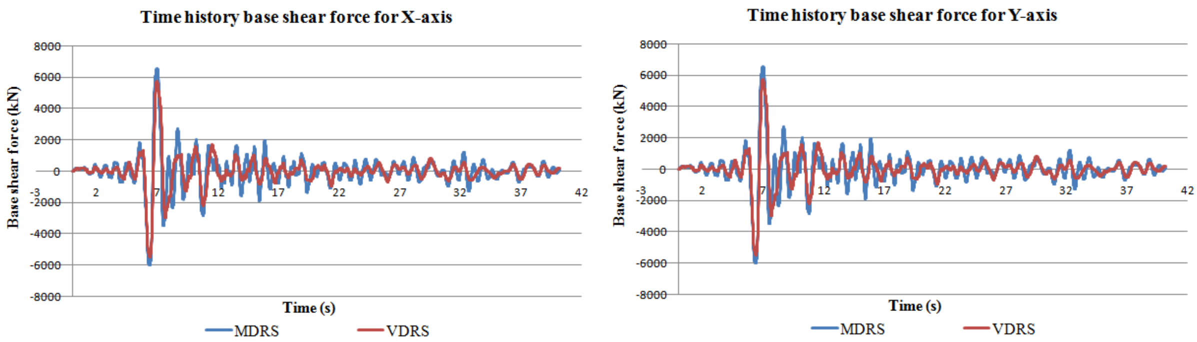


Figure 8: Comparative time history base shear force

Comparative time history response in terms of base shear for the two retrofitted system indicates higher values for base shear in MDRS.

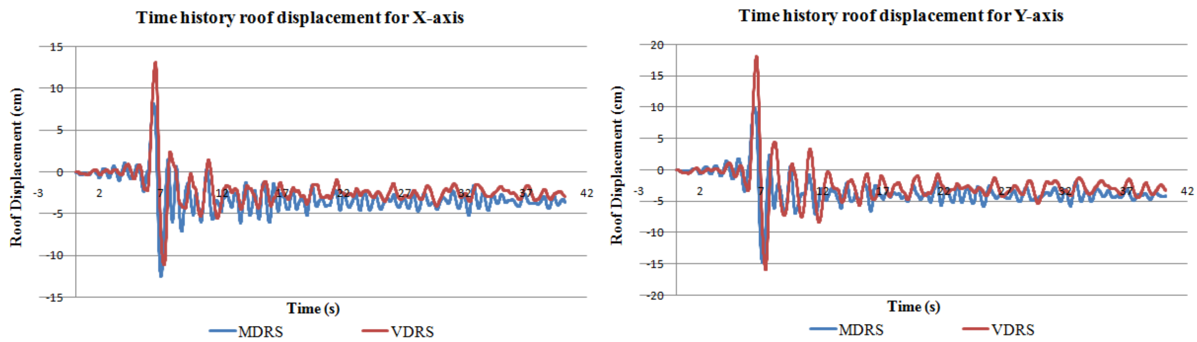


Figure 9: Comparative time history roof maximum displacements

Selected results of Figure 9, time history of top displacements, correspond to both retrofitted buildings, revealing that displacements for viscous damper systems are larger for the higher magnitude of the accelerogram, but important damping provided by VD minimize displacement values in time. Maximum peak displacements for VDRS are 15.91cm (y), 11.3 (x) and for MDRS 14.75cm (y) and 12.49 (x).

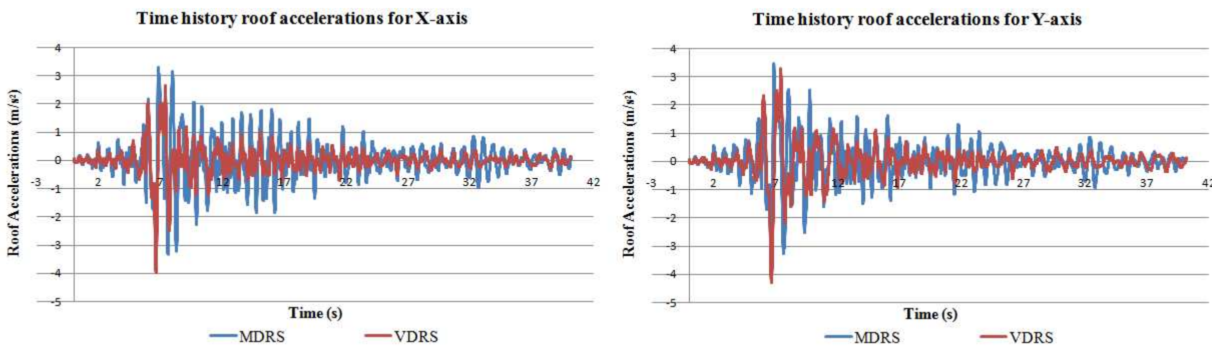


Figure 10: Comparative time history roof maximum accelerations

If roof displacements for the two retrofitting systems have closed values, roof accelerations are visibly reduced for VDRS comparing with MDRS – Figure 10.

Although metallic dampers have been shown to be effective in reducing interstory drifts, some studies have found that, in many cases, the use of metallic dampers may cause increases in floor accelerations due to the added stiffness, which may negatively affect seismic behavior of nonstructural components. [3] This point of view is demonstrated in Figure 10.

4 CONCLUSIONS

This paper demonstrates the need of seismic retrofitting for existing RC framed structures designed according to out of date Romanian codes. The building considerred in this paper doesn't achieve all the requirements afferent to current seismic code: strength, stiffness and ductility.

To improve the seismic response for the existing RC structure, the paper proposes two innovative retrofitting systems with passive energy dampers: metallic dampers and viscous dampers.

MD used in this study is a short bolted dissipative link placed in an eccentrically braced frame. Because MDRS doesn't involve the need for special inovative system or materials, it is more cost-effective than VDRS, which are innovative and expensive systems.

Time history analyses reveal the improved seismic behaviour for RC frames when installing passive dampers in the structure. Viscous dampers are most efficient in lower values for accelerations.

Both retrofitting systems provide nearly the same important stifness to the structure.

An important dissadvantage for vertical removable short links used in this study as metallic dampers, is their need to be replaced after a major earthquake , unlike VD that have the possibility to reach the initial characteristics (geometrics and damping constant) after an earthquake.

The final conclusions of this paper is that both methods are efficient for seismic retrofitting: MDRS is more cost – effective, and VDRS has a better seismic behaviour. Because of this, we recommend using VDRS for important structures, like hospitals or buildings which houses sensitive technologies (especially because of the lower accelerations) and MDRS for ordinary buildings.

REFERENCES

[1] *** P13-70, *Normativ pentru proiectarea construcţiilor civile şi industriale din regiuni seismic*, Editura Tehnica, Bucuresti, 1971.

[2] A.M. Gramescu, A. M. D. Barbu, *Repararea si consolidarea constructiilor*, Editura Agir, Bucuresti, 2008.

[3] *** P100-2006, *Normativ de proiectare seismică*, Cap.3, Cap.4, p.4.2-4.15, Cap.6, p.6.1-6.10, p.6.16-6.20, Anexa A, p.5, Anexa D, 2006.

[4] *** CSI Analysis Reference Manual for SAP2000, Computers & Structures Inc., Berkeley, California, April 2009.

[5] *** Eurocode 8: *Design of structures for earthquake resistance – Part 1: General rules, seismic actions, and rules for buildings*, 2004

[6] F.S. Florea, L. E. Rosu, *Enhanced Seismic Resistance of Steel Structures Using Passive Energy Dissipation Devices*,The 3rd Conference of the Young Researchers from TUCEB, Bucharest, 2012.

[7] *** FEMA 356, *Prestandard and Commentary for the Seismic Rehabilitation of Buildings*, Federal Emergency Management Agency, 5.1-5.54, 9.1-9.33, 2000.

[8] R. E. Vargas, *Seismic Response of Metallic Systems with Metallic and Viscous Dampers*, Student Research Accomplishments Volume: 2004-2005.