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EFFICIENCY OF USING VISCOUS DAMPERS FOR MULTI-STOREY STEEL STRUCTURES SUBJECTED TO SEISMIC ACTIONS

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Abstract. *The use of energy dissipation devices is an efficient method to enhance performance of buildings at all hazard levels by adding damping and/or stiffness. Considering the reduction of seismic response and also the cost reduction, it is expected that their utilisation to be more frequent in the future. The paper analyses the effectiveness of linear viscous dampers (velocity-dependent devices) for reducing the seismic response of a 13-story steel building, which is designed according to EC 8 – National Annex, located in seismic conditions of Bucharest city area. The paper analyses and compares three types of structural systems: a dual steel structure with concentrically braced frames (CBF) and moment resisting frames, a dual steel structure with eccentrically braced frames (EBF) and moment resisting frames and a dual steel structure equipped with viscous dampers providing an additional damping level of 27% out of the critical level. The comparative terms are values of the structural response: top displacement, absolute top acceleration and base shear force, vibration period and steel consumption obtained by nonlinear time history analysis. The conclusions of the article will be supported by a set of results obtained by performing nonliniar-dynamic analyses using accelerograms compatible with the design spectrum for the considered location.*

1 INTRODUCTION

The aim of this paper is analyzing a 13 story steel building considering 3 structural configurations, to highlight the most advantageous solution regarding material consumption and seismic performance. To analyze the behaviour of each structural system and to determine the most effective solution, a regular steel structure is considered with three structural systems:

- Structure 1 (Figure 1.a and Figure 2.a) is a dual steel structure with concentrically inverted V braced frames (CBF) and moment resisting frames (MRF), referred to as CBS.
- Structure 2 (Figure 1.b and Figure 2.b) is a dual steel structure with MRF and eccentrically braced frames (EBF) with vertical short links referred to as EBS.
- Structure 3 (Figure 1.c and Figure 2.c) is a dual steel structure with concentrically inverted V braced frames and MRF, equipped with viscous dampers providing an additional damping level of 27% out of the critical level, referred to as VDS.

Concentrically braced frames are vertical truss systems that provide stiffness, strength and ductility to the structural system. The seismic energy is dissipated through the inelastic behaviour of the braces that exhibit axial deformations. The rest of the structural members are provided to behave in the elastic range. The main disadvantage for CBF is the buckling of the compressive braces, that leads to unpredicted hinges in the structural elements, affecting the stiffness and resistance of the frame.

Eccentrically braced frames have been defined as systems that merge the properties of the moment resisting frames and the properties of concentrically braced frames. An EBF can provide structural stiffness similar to that of CBF. Links subjected to lateral loads deform inelastically, showing good energy dissipation capacity and high ductility, characteristics found in moment resisting frames. EBF resist to horizontal loads by axially loaded elements, but they are designed to exhibit first plastic deformations in links, provided to yield in bending moment or shear force, according to their length. [1] The design prescription specific for EBF provide that connections and the other elements of the frame (structural elements outside links) are designed to remain in the elastic range. For a global behaviour without significant degradation of strength and stiffness to severe cyclic loading, in properly designed EBF only links will yield, except for base columns.

Viscous dampers (VD) are passive energy dissipation devices. The damper force depends on the relative velocity between the two ends of the damper and can be expressed using Eq.(1)[3]:

$$F_{disip} = c \times \nu^{\alpha} \tag*{(1)[3]}$$

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.

For a linear VD α=1 and the force increases linearly with the velocity. They develop a large force proportional to the displacement and they can dissipate a large amount of energy.

During the last years, viscous damper were used for the strengthening of existing structures due to their capacity to increase the damping of a structure, but they can also be used to new structures and the tendency is for their application to a large extent. VD have been used successfully to increase damping ratio for structures where the use of other types of devices was difficult or was not efficient. [2]

2 DESCRIPTION OF ANALYZED STRUCTURES

2.1 Analyzed structures

The structures have three spans (of 6.00m) and four bays (of 6.00m) and 13 levels, each of 3.80m high. The steel used is S355 (f_y=355N/mm^2). Section shapes are: columns – Malta cross shape (MC) - welded section, main beams – double – T section (IPE profile and WS-welded sections) and braces - pipe (CHS) sections. Floors are made of reinforced concrete slabs.

The loads considered for the analysis and the design requirements are taken in accordance with EN Eurocodes adapted in environmental conditions in Romania.

The structure was designed according to EC 8 – National Annex and P100-1-2006, located in seismic conditions of Bucharest city area using the equivalent static seismic force method. According to seismic zoning maps (P100-1-2006) for structure location the corresponding prescriptions are: design ground acceleration 0.24g, with corner period of 1.6s (T =1.6s), for a seismic action with the mean return period of 100 years (provided in P100-1-2006 for structural design to Ultimate Limit State). The maximum dynamic amplification factor for the horizontal ground acceleration of the structure is (according to P100-1-2006 code) βo=2.75.

For structural analysis was used SAP2000 program.

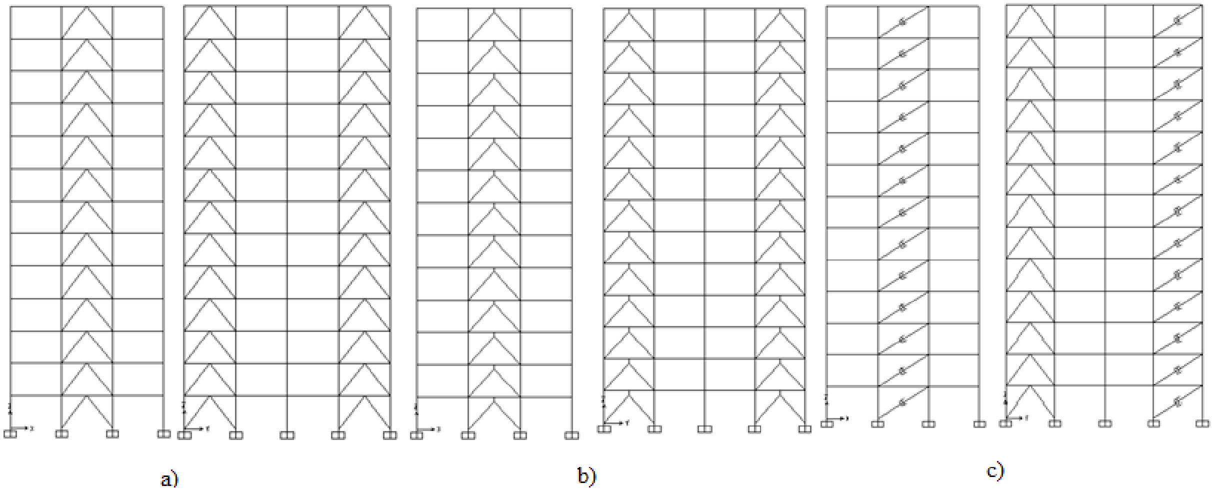

Figure 1: Structural systems – elevation view: a) Structure 1-CBS; b) Structure 2-EBS; c) Structure 3-VDS

To verify the proper seismic behaviour for the structural systems CBS and EBS, a nonlinear static analysis (pushover) was performed. The nonlinear behaviour of structural members was modelled using plastic hinges and acceptance criteria according to FEMA 356: hinges for columns are due to axial force-bending moment interaction, hinges for braces are due to axial force, hinges for beams are due to bending moment and hinges for vertical short links are due to shear force.

For the dynamic nonlinear analysis was used the North-South component of March 4th, Vrancea (Romania) 1977 accelerogram, recorded at INCERC, Bucharest, scaled by a factor of 1.2 in order to correspond to a mean return period of 100 years.

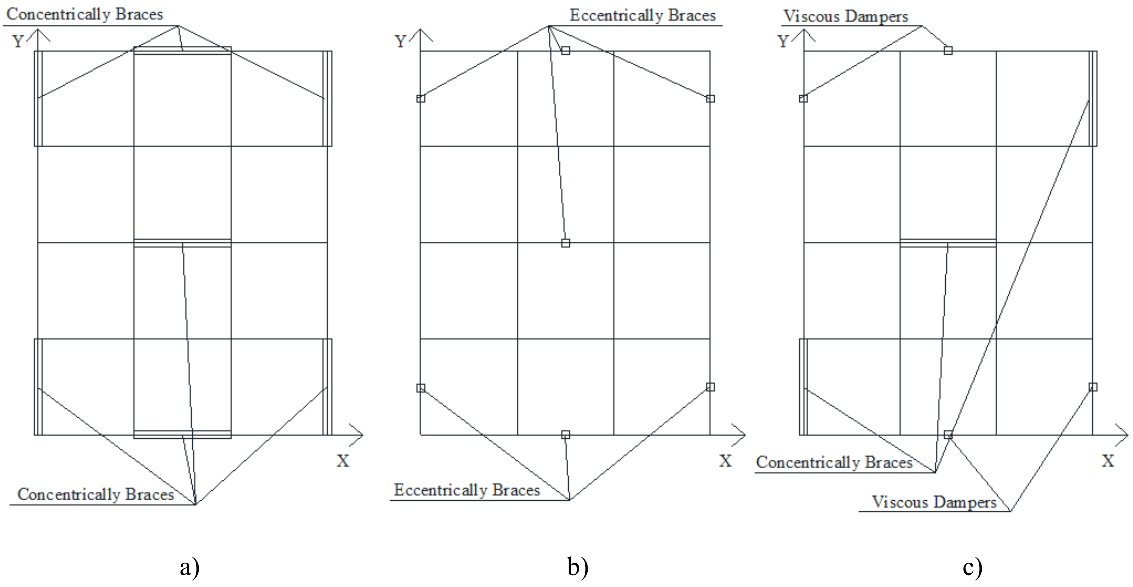

Figure 2: Structural systems-plan view: a) CBS; b) EBS; c) VDS.

A set of 20 nonlinear-dynamic analysis were performed using accelerograms compatible with the design spectrum for the considered location. The accelerograms were generated in order to obtain a set of earthquakes with different degrees of peak ground acceleration, compatible with the design spectrum (Figure 3).

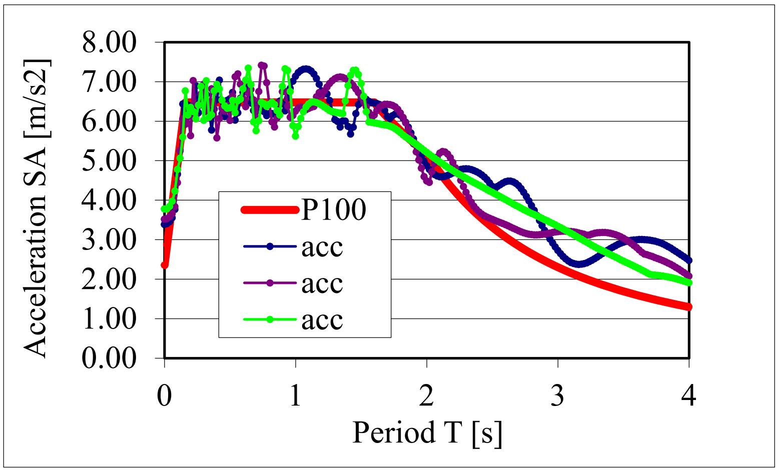

Figure 3: The elastic spectrum and the generated spectrum for three synthetic accelerograms.

To highlight the contribution of VD in dissipating the seismic energy, the structure with VD was subjected to additional nonlinear dynamic analysis using the Vrancea 1977, N-S, accelerogram, recorded at INCERC, Bucharest, scaled by the factor of 1.6 corresponding to a mean return period of 475 years, which will be recommended in the near future for the structures classified in the 2nd importance category (according to P100-1-2012).

2.2 Design of linear viscous dampers

Viscous dampers were placed according to Figure 2c, in order to replace some of the concentrically braces from the CBS structure. There are two viscous dampers on each principal direction on each level. These are placed on the perimeter frames in a diagonal position (Figure 1c). Structural elements of the building were calculated using a seismic force corresponding to a damping ratio of 30% from which 3% represents the natural damping ratio and 27% represents the additional damping ratio. The base shear force is affected by the factor η described in Eq. (2)[3, 5] corresponding to the equivalent damping ratio (ξ_{eq27}=27%).

$$\boldsymbol{\eta} = \sqrt{\frac{\mathbf{10}}{\mathbf{3}+\boldsymbol{\xi}_{\boldsymbol{eq27}}}} = \mathbf{0.57} \tag{2)[5}$$

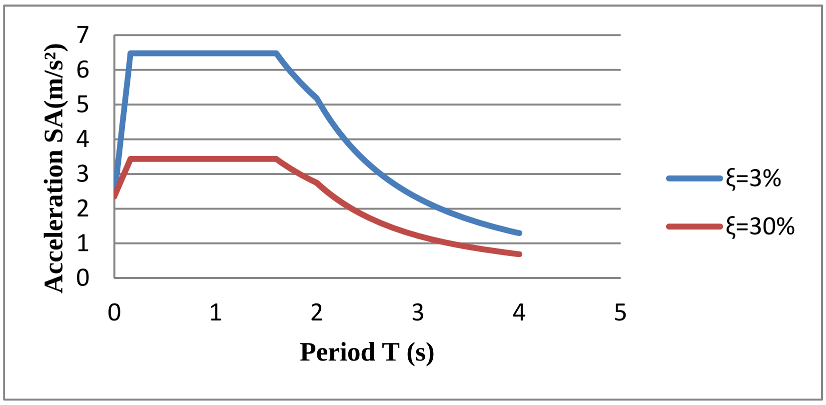

Figure 4: Reduction of design seismic spectrum due to factor η.

To determine VD characteristics, is used the methodology described in FEMA 356. The Eq.(3) results from equalising the energy dissipated in one complete oscillation cycle by the actual structure to the energy dissipated by an equivalent viscous system [3].

$$\xi_{eq} = \frac{E_D}{4\pi E_S} \tag{3)[3}$$

where: E_D is the energy dissipated by the devices in an oscillation cycle and is calculated as the sum of work done by each device in that cycle using Eq.(4); E_S is the maximum potential energy of deformation calculated with Eq.(5) [3].

$$E_D = \sum_J(W_j) = \sum_j \frac{2\pi^2}{T} c_j \delta_{rj}^2 \tag{4)[3}$$

where: T – is the fundamental mode period for the analyzed direction; c_j – is the damping constant of linear viscous damper „j”; δ_{rj} – is the relative displacement between the ends of device „j”.

$$E_S = \frac{1}{2}\sum(F_i\delta_i) \tag{5)[3}$$

where: F_i – is the inertia force at floor level „i”; m_i – is the structural mass at level „i”; a_i – is the acceleration at floor level „i”.

Damping constants of devices c_j are calculated using Eq.(6)[3] where c_0 is a reference value and k_j are coefficients chosen by the designer. In this specific case, all k_j coefficients are assigned to value 1 (k_j = 1)[4].

$$c_i = c_0 k_i \tag{6)[3}$$

By replacing Eqs.(4) and (5) in Eq.(3) one can obtain Eq.(7) to calculate damping constant *c* of viscous dampers:

$$c = \frac{\xi_{eq} 4\pi \frac{1}{2}\sum_i(F_i\delta_i)}{\frac{2\pi^2}{T}\sum_J \delta_{rj}^2} \tag{7}$$

The damping constant *c* of viscous dampers will be calculated using Eq.(7) from the condition for the equivalent damping ratio (ξ_{eq}), due to the action of the supplemental viscous dampers, to be equal with 27% of the critical damping ratio.

The resulted values for the damping constants of devices is: c_x=25800 kNs/m (X direction) and c_y=33200 kNs/m (Y direction).

3 ANALYSIS RESULTS AND OBSERVATIONS

3.1 Modal analysis

Table 1 illustrates the values for the first two mode of vibration – period:

		CB*S*	EB*S*	VDS
Mode 1 (Transversal-X)	Period - T	1.418	1.441	1.82
Mode 2 (Longitudinal-Y)	Period - T	1.322	1.333	1.17

Table 1: Eigenvalues for the first mode of vibration for each direction.

On the X direction, the increased values for VDS are explained by the fact that VD provide damping for the structural system, but they don't provide stiffness. They improve the seismic performance of the structure by absorbing the energy induced by the defined earthquake. In Table 4 are presented the comparative values of steel consumption for the analyzed structures.

Structure	CBS	EBS	VDS
Steel consumption	945t	888.3t	816.3t

Table 4: Steel consumption for the analyzed structures.

3.2 Static nonlinear analysis results

For the push-over analysis of CBS and EBS, the roof displacement- base shear force curve was plotted to highline the occurrence of successive plastic hinges (Figure 5-6), where dt represents the target displacement obtain by the bilinear procedure described in P100 and EC8 and Fy represents the yield force of the structure.

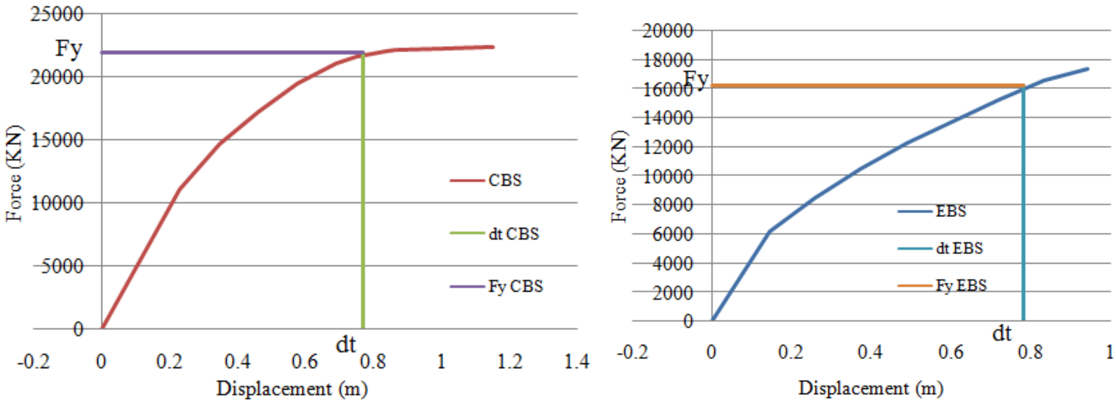

Figure 5: Pushover curves -X direction- for analyzed structures.

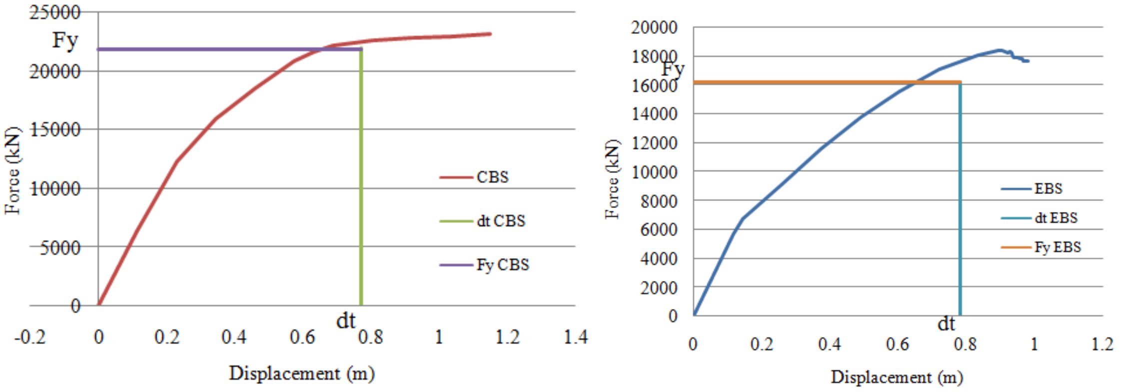

Figure 6: Pushover curves -Y direction- for analyzed structures.

The static pushover curves for the two compared structures show that CBF provide more resistance, reflected by the bigger values for the base shear and more stiffness. The disadvantage for the CBS is that almost all the buckled braces hinges exceed life safety limit, and they need to be replaced after a severe earthquake. On the other hand, for EBS, hinges in links don’t exceed the Life Safety limit.

As a general push-over analysis result, we can conclude that the dual system with CBF exhibits more resistance and stiffness than the one with EBF, but with limits because of the buckled braces. EBS has a controlled plastic mechanism due to dissipative links, and of the elastic behaviour of other structural elements. For both structures (CBS and EBS) the structural elements have an elastic behaviour.

3.3 Dynamic nonlinear analysis results

The structural seismic response in terms of maximum top displacement, maximum absolute top acceleration and base shear force (BSF) resulted from the nonlinear dynamic analysis performed using Vrancea (Romania) 1977, N-S, accelerogram, recorded at INCERC, Bucharest, corresponding to a mean return period (MRP) of 100 years, are presented in table 3, table 4, Figure 6, Figure 7 and Figure 8. The results are presented for the node 397 located on the top level of a perimeter frame.

Response value X direction	MRP 100years			MRP 475years
	CBF	EBF	VDS	VDS
Max. top displ. (m)	0.712	0.434	0.496	0.637
Max. abs. top accel.(m/s^2)	6.63	5.44	5.26	6.74
BSF (kN)	18580	14110	15690	19720

Table 3: Structural response values for transversal - direction X.

Response value Y direction	MRP 100years			MRP 475 years
	CBF	EBF	VDS	VDS
Max. top displ. (m)	0.694	0.399	0.766	0.818
Max. abs. top accel.(m/s^2)	7.07	5.29	7.01	10.83
BSF (kN)	19060	15440	15540	17990

Table 4: Structural response values for longitudinal - direction Y.

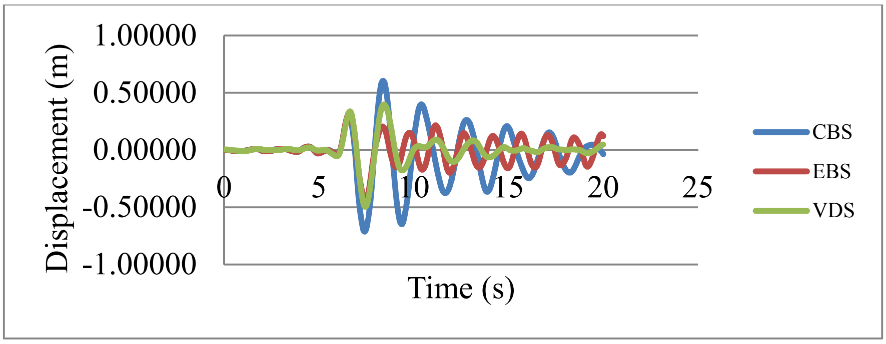

Figure 6: Representation for time variation values of top displacement (X direction).

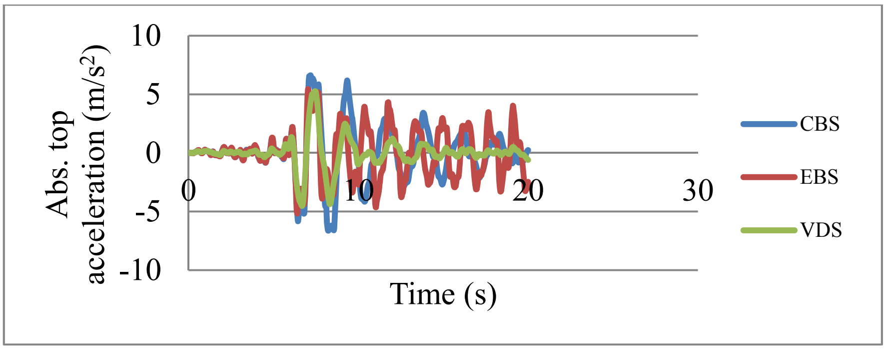

Figure 7: Representation for time variation values of abs. top acceleration (X direction).

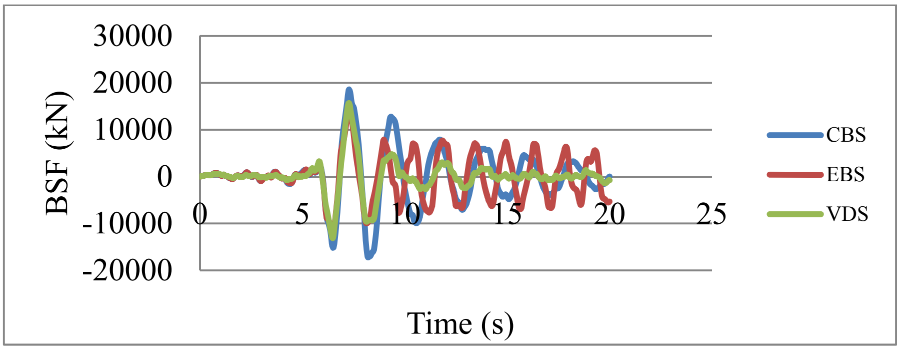

Figure 8: Representation for time variation values of base shear force (X direction).

The most efficient structure in terms of maximum top displacement and base shear force is the EBS, and the most efficient in terms of max. abs. top acceleration is the VDS. The CBS system is the less efficient, its only advantage being the higher stiffness provided compared with the other two structural systems. For the VDS all structural elements, excepting braces, have an elastic behavior and the response parameters are comparable with the EBS response parameters on transverse direction. On longitudinal "Y" direction it can be observed (Table 1) that the VDS has more stiffness comparing to the transverse direction and for this reason, the seismic response in terms of max. top displacement are comparable with the seismic response of CBS structure. Analyzing table 3 and table 4 one can observe that for a seismic action corresponding to a MRP of 475 years the seismic behaviour of VDS is still good , with a controlled plastic mechanism due to VD, and comparable with the seismic behaviour of CBS for the seismic action with a MRP of 100 years.

The values of seismic response parameters for the analyzed structures for all the synthetic accelerograms are presented in Figure 9, Figure 10 and Figure 11.

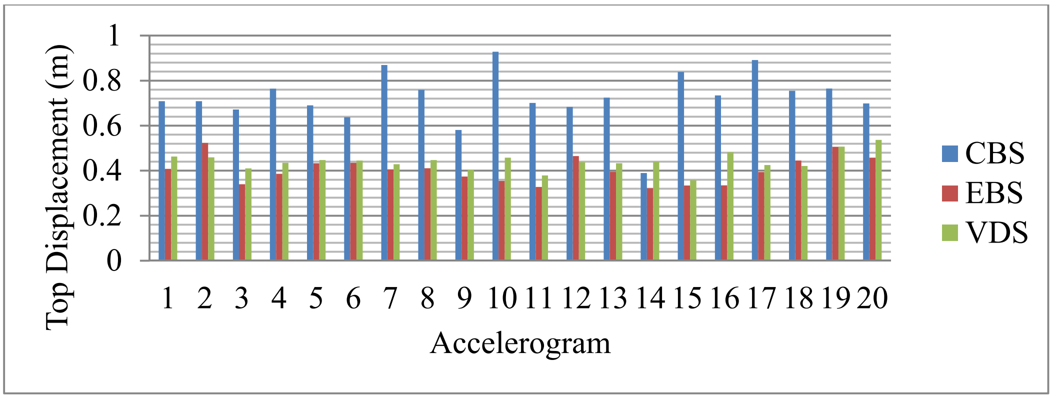

Figure 9: Max. top displacement for the analyzed structures.

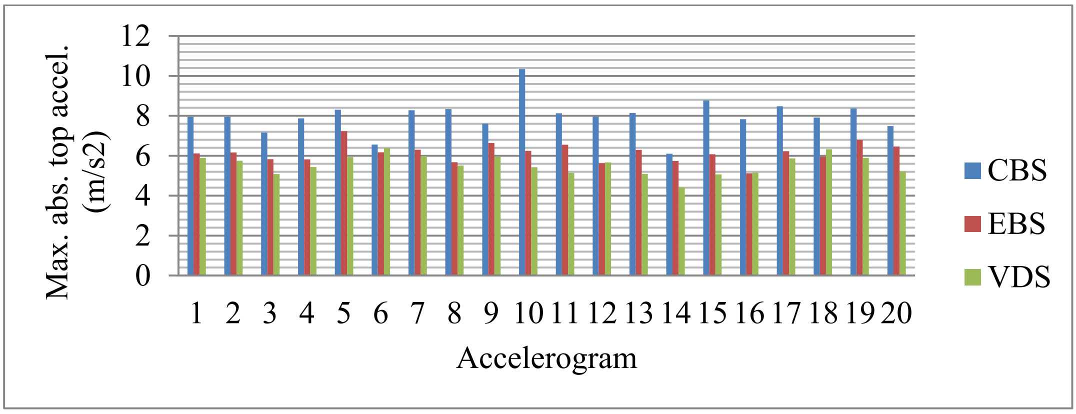

Figure 10: Max. abs. top acceleration for the analyzed structures.

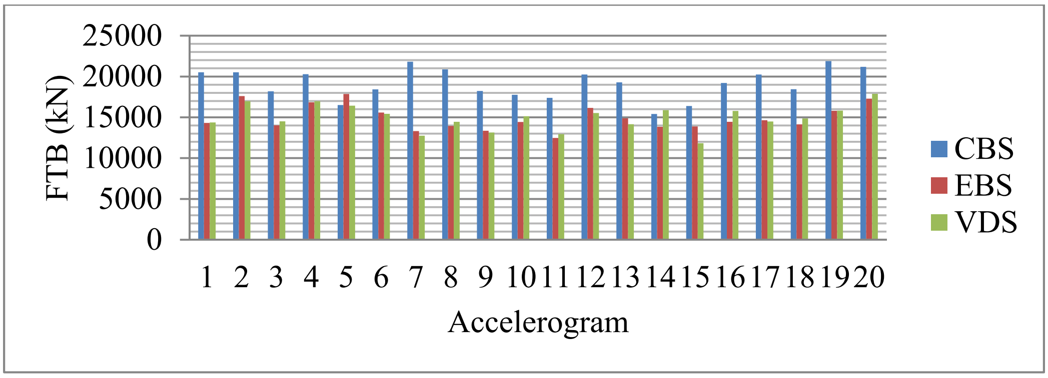

Figure 11: Max. base shear force for the analyzed structures.

The time-history response reveal smaller values for maximum roof displacements and maximum roof accelerations for the EBS compared to CBS. The VDS system is the most advantageous in terms of absolute top accelerations, and regarding displacements and base shear force it is comparable with the EBS system. The number of hinges in structural elements (beams and columns) for VDS are reduced comparing with the other two systems, so the structure doesn’t need rehabilitation after a major earthquake.

4 CONCLUSIONS

Comparing the two traditional steel structures – CBS and EBS, we can say that the most efficient is the second one, in terms of material consumption and ductility.

The VDS is the most economicaly efficient structural system. The steel consumption decreases with 13% compared with the CBS structure and with 8% compared with the EBS structure.

The seismic response for VDS system is clearly advantageous. After an earthquake VD do not need to be replaced due to their possibility to reach the initial characteristics (geometrics and damping constant).

One can observe that linear viscous damper can be succesfuly used as additional energy dissipation devices for new structures. Energy dissipation throught inelastic incursions of some structural elements (natural damping and concentrically braces), is indispensable in case of a major earthquake and for this reason linear viscous dampers are not designed to dissipate by themselves the entire seismic energy. They bring additional damping to the structure being very usefull when it is required to decrease displacements and accelerations due to seismic action, and also can reduce efforts in structural elements. Fluid viscous dampers also presents advantages comparing to traditional systems, for their ability to remain undamaged for a large number of loading-unloading cycles.

We can conclude that the most economicaly efficient structural system is VDS because it doesn't need structural rehabilitation after an earthquake. EBS seems to be the most advantageous between the traditional systems, because it has less steel consumption, important ductility and a better time history behaviour.

Still, an opened issue it is the achievement, based on further research, of on optimal placement of energy dissipation devices in order to reduce the number of viscous dampers in the structure. Further theoretical researches on the behaviour of structural systems with dual frames and nonlinear viscous dampers should be performed so that all the disadvantages of using concentrically braces to be reduced. It appears of interest realization of theoretical researches on the behaviour of dual steel structures with eccentrically braced frames and with additional linear and nonlinear viscous dampers.

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