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STRUCTURAL CONTROL SYSTEMS FOR BASE ISOLATED BUILDINGS

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ABSTRACT

Current seismic design philosophy accepts the occurrence of significant amount of damage during high intensity earthquakes. Important financial resources are spent for providing building ductility, for post-seismic rehabilitation works (both structural and non-structural) and breaks in functionality are accepted.

One alternative, widely extended worldwide from one year to another, is based on structural response control using base isolation and damping devices. These solutions comprise decoupling the infrastructure from superstructure (base isolation) as well as increasing the structural damping by passive, active or semi-active dampers and their combinations.

This paper analyses comparatively the effectiveness of various control devices and systems on given seismic demands of Bucharest, using simplified two degree of freedom models. Base isolation through elastomeric devices and supplemental damping devices at base level are briefly analyzed.

A case study is examined within the paper, namely a medium rise RC building (GF+5 Stories). Effectiveness of response control devices is analyzed using the seismic demand imposed by Vrancea 1977 March 4th earthquake (dynamic time history 3D analysis).

Conclusions are drawn for optimizing the use of structural control systems complying with seismic conditions of Bucharest.

INTRODUCTION

Improvement of seismic performance of actual building stock is currently a main item for seismic countries. This target can be achieved through "classic" solutions or through new and innovative technologies, involving passive, semi-active or active structural control. Materials used for structural control and devices are still subject to study and develop worldwide. Each structure can be dynamically analyzed as a function of three main parameters: mass, damping and stiffness. Modification of any of these functions in order to decrease the seismic response to a severe ground motion is called structural control. Passive systems use the energy of earthquake and their characteristics are usually set and

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constant during seismic excitation. Active systems use an additional energy from an exterior source. Their characteristics are to adapt during seismic excitation in order to decrease the response. However, additional forces into the structure are included, and functionality is strictly related to the exterior energy source. As an alternative, semi-active systems combine the advantages the passive and active devices, by providing the adaptive response control with minimal exterior energy, and, even in absence of external power these devices perform as passive control systems.

CHARACTERISTICS OF GROUND MOTIONS IN ROMANIA

Performance through control of response is highly dependant to the characteristics of local seismic motions especially on spectral composition. Main source of earthquakes in Romania is located in Vrancea Mountains. It produces around 3 major events (M>7.0, Richter scale) each century. These earthquakes have a depth ranging from 70 to 150 km. Their particularity consists in high displacement demands and dynamic amplification effects at long periods. A 1977, March 4th, N-S component, SA vs. SD spectra[1], is given in Fig 1 a), as well as velocity spectra, Fig 1 b), for various damping levels.

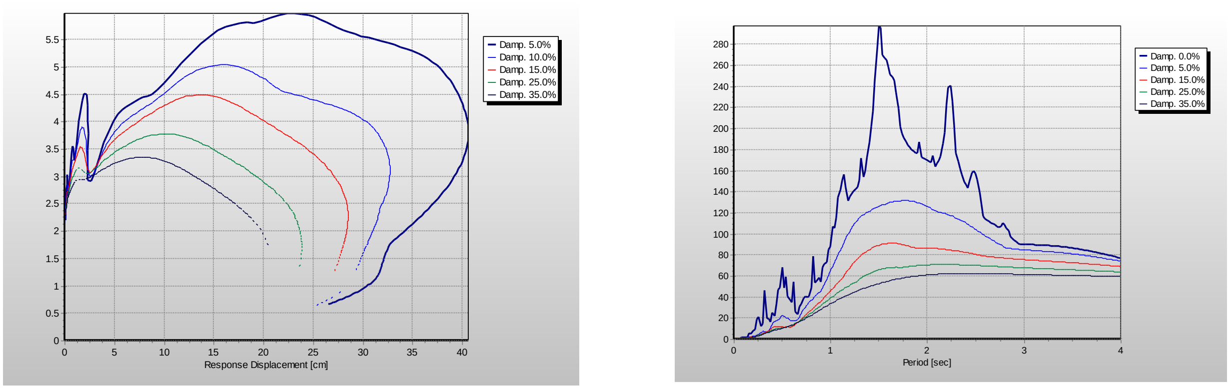


Fig 1 a) SA vs. SD spectra

b) Velocity spectra

OBJECTIVES OF THIS STUDY

This study aims to examine the effectiveness of passive and semi-active control systems for a typical mid-rise RC building in Bucharest.. The solution of structural control consists on base isolation, using linear rubber bearings and additional passive and semi-active dampers. Optimal levels of damping were found through analyzes carried out on a simplified 2 degrees of freedom model and results were considered through analyzes of the mid-rise building. Calculations for passive and semi-active damping devices were performed. Comparison of output parameters like base displacement, roof acceleration and maximum force carried by the dampers was made and conclusions are drawn through the end of this paper.

THE SIMPLIFIED 2 DEGREE OF FREEDOM MODEL

As we can observe in Fig 2), the two degrees of freedom (2 DOF) of the system are mass lateral translations. It is considered that the above simplified system is derived from a fixed base single degree of freedom system, whose base is then isolated. The fixed base system has a natural period of 0.93 seconds and an inherent level of damping of 5 % from critical damping. As a result of base isolation, the fundamental period of isolated system is increased up to 3.39 sec. The isolation system itself has low natural damping (taken to be zero). The isolated system is provided with a controllable energy dissipation device (controllable damper), attached on the base and to the ground. Hereby, obtained system is subjected to an imposed base movement described by Vrancea 1977 acceleration, N-S component, INCERC, Bucharest.

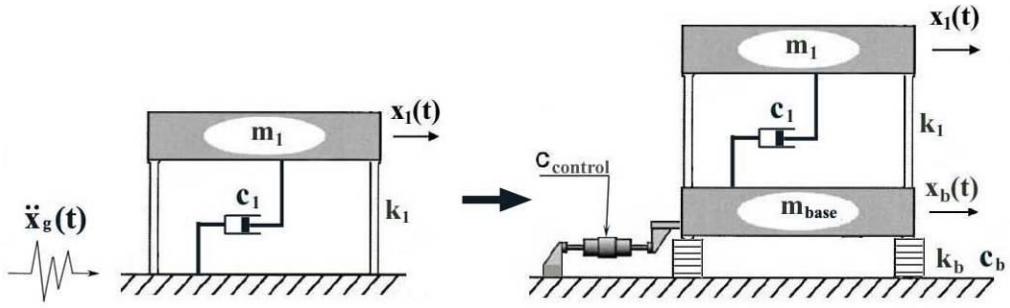


Figure 2) Simplified 2 degrees of freedom model

The system stiffness is constant in time. The damping level of the controllable damper is varied in time according to the control strategies that will be described below.
The response of the system is governed by the following system of equations:

$$M \cdot \ddot{x} + C \cdot \dot{x} + K \cdot x = -M \cdot I_{2x1} \cdot \ddot{x}_g, \quad (1)$$

where:

M is the mass matrix: $M = \begin{bmatrix} m_b & 0 \\ 0 & m_1 \end{bmatrix}; \quad m_b = 331 \, {kN \cdot s^2}/{m}, \; m_1 = 3740 \, {kN \cdot s^2}/{m};$

K is the stiffness matrix: $K = \begin{bmatrix} (k_b + k_1) & -k_1 \\ -k_1 & k_1 \end{bmatrix}; \; k_b = 14994 \, {kN}/{m}, \; k_1 = 170713 \, {kN}/{m};$

C is the damping matrix: $C = \begin{bmatrix} (c_b + c_1 + c_{cont}) & -c_1 \\ -c_1 & c_1 \end{bmatrix}; \; c_b = 0, \; c_1 = 2527 \, {kN \cdot s}/{m}.$

Later on, from numerical considerations, the damping matrix will be decomposed as it follows:

$$C = C_{natural} + C_{control} = \begin{bmatrix} (c_b + c_1) & -c_1 \\ -c_1 & c_1 \end{bmatrix} + \begin{bmatrix} c_{cont} & 0 \\ 0 & 0 \end{bmatrix} \quad (2)$$

and the equation of motion becomes:

$$M \cdot \ddot{x} + C_{natural} \cdot \dot{x} + K \cdot x = -M \cdot I_{2x1} \cdot \ddot{x}_g - C_{control} \cdot \dot{x}. \quad (3)$$

For MATLAB implementation, the above matrix equation of motion will be converted into a state-space form. First control strategy employed in this paper consists in constraining the force developing in controllable damper to remain inferior or equal with a prescribed value. The constitutive law for the semi-active control damping device is the following:

$$F_{cont}(t) = \begin{cases} c_{cont} \cdot \dot{x}_b(t), \text{if } \; c_{cont} \cdot \dot{x}_b(t) \le F_{lim}; \\ F_{lim}, \; \text{ if } \; c_{cont} \cdot \dot{x}_b(t) > F_{lim}. \end{cases} \quad (4)$$

In the above relation, F_{cont} is the control force; F_{lim} is the limit value of control force and $\dot{x}_b$ is de base velocity. The viscous damping coefficient of the damper c_{cont} is constant for the first branch of the constitutive law. In the case of the second branch, c_{cont} will be varied so that the control force remains equal with F_{lim}. The damping coefficient value in the first branch and the control force limit value will be established by a parametric study with F_{lim} / F_{max} and c_{cont} / c_{cr} as main parameters, examining several response measures such as: base displacement, relative displacement of the superstructure, absolute acceleration of the superstructure, control force and shear force above the base level. F_{max} and c_{cont} in the parametric study, represent the maximum force that would be achieved if the damping device would have a fully linear-viscous behavior and respectively, damping coefficient value for the first branch of constitutive law. c_{cr} is the critical damping coefficient for a SDOF system having the mass and stiffness equal with the total mass of the base isolated system and base isolation stiffness respectively. The peak values for the observed response measures are represented on Fig 3).

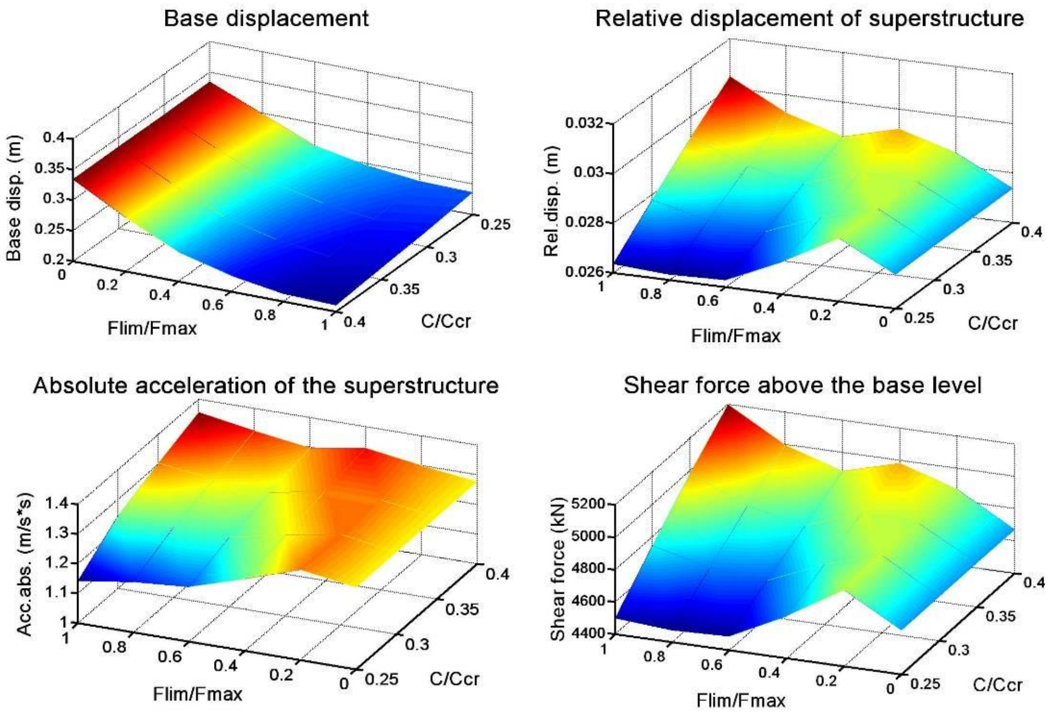


Fig 3) Peak values for control parameters

After observations on response of the system for various values of the two parameters the optimal values will be assumed: F_{lim}/F_{max}=0.4 and c_{cont}/c_{cr}=0.35.
The second control strategy is based on the use of fuzzy-logic to modify the damping coefficient of the damper. Displacement and base velocity are continuously monitored by making samples and readings using a sensor. The two output measures are then transmitted to a controller. The controller uses a fuzzy inference system to make decisions about the value of the damping coefficient c_{cont} Fig 4).

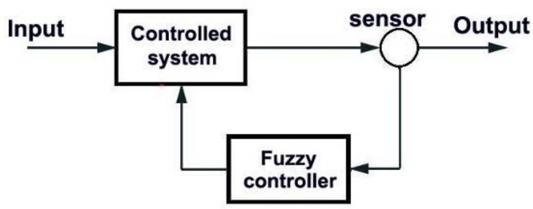


Fig 4) – Dynamic system equipped with fuzzy controller

The whole behavior of the controller is resumed by the control surface showed on Fig 5). The controller operates with normalized measures. Base normalized displacement is the ratio between the base displacement of the 2 DOF systems and spectral displacement for a SDOF system having the mass and fundamental period of the 2 DOF systems. Base normalized velocity has an analogous definition. c/c_{max} is the ratio between the controlled damping coefficient and its maximum value. $c \in (0.1 \ldots 1) \cdot c_{max}$ and $c_{max} = 0.35 \cdot c_{cr}$. c_{cr} is the critical damping coefficient of the SDOF mentioned earlier.

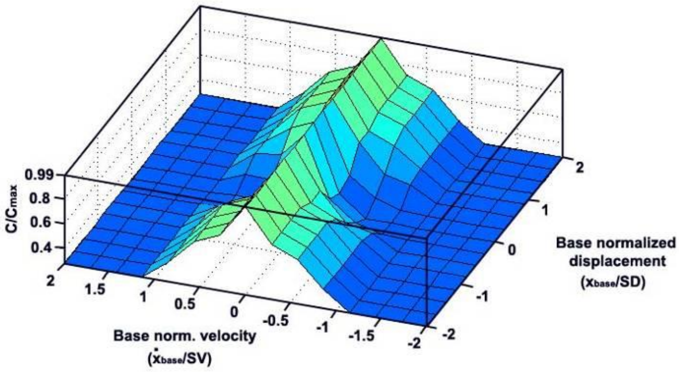


Fig 5) – Control surface

The peak response values for the passive damping device case (c=35%) and the two semi-active damping device cases are presented on table 1.

Table 1 – Peak response values for passive/semi-active cases

Peak value	Passive device	First strategy	Second strategy
Base displacement (m)	0.216	0.250	0.260
Relative displacement (m)	0.028	0.027	0.026
Superstructure .absolute acceleration (m/s^2)	1.269	1.236	1.17
Base Shear Force (kN)	4857	4614	4479
Control force	3516	1405	1786

The following conclusions came out from this study:

The differences between all peak response values (except damper force) for the three cases are insignificant. That means that an improved response can be obtained for a lower level of the base damping force, i. e. for smaller but semi-active dampers.

Due to numerical simplicity and practical considerations, further on, the first strategy will be considered.

CASE STUDY – MID RISE RC BUILDING

Model outline

The model analyzed is a 5 stories RC frame building with 4 spans on transversal direction of 6,00 m each, and 6 spans on longitudinal direction 4 of 6,00 m and 2 of 4,00 m. Story height is 3,00 m. Configuration of the model is given in Fig 6.

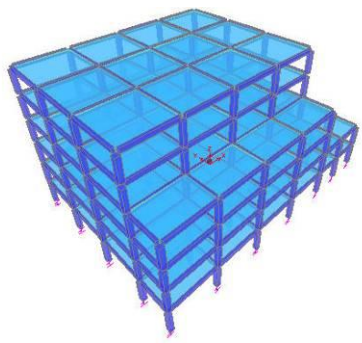


Fig 6) – Outline of the model

Beams have rectangular cross sections of 25x50 cm; while the columns are square with a section of 50x50 cm. Gravity distributed loads have an intensity of 11 kN/m^2. Model was subjected to linear time history analyses, using the 1977 March 4th earthquake, N-S component and to conventional seismic force using P100/92 seismic design code [2]; Computer simulation was run using software RAM-PERFORM 3D;

Results for fixed base hypothesis

Dynamic analyses were performed for the fixed base model. Also a pushover case was performed. The results are briefly synthesized on table 2, while the drifts and pushover capacity curve are plotted on Fig 7 a) and b).

Table 2 – Results for fixed base model

	Period (sec)	Roof acceleration(m/s^2)	Post elastic response
Transversal direction	0,88	6,10	Plastic hinges located on end of the beams and at the base of columns
Longitudinal direction	0,93	5,87	

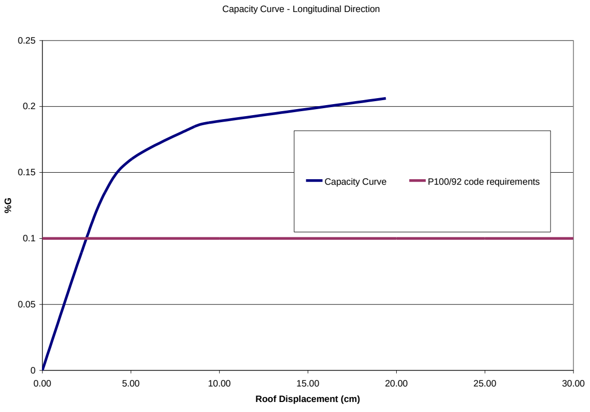


Fig 7 a) Capacity curve of fixed base model

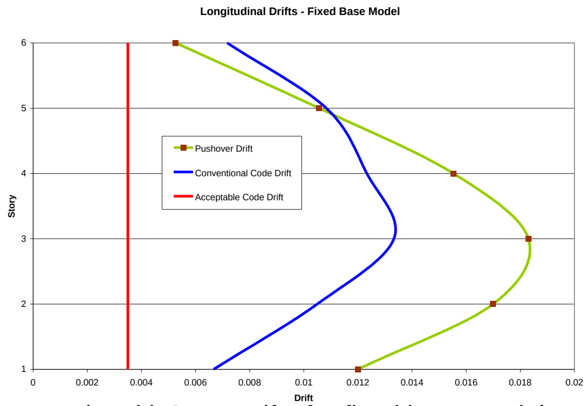


Fig 7 b) Story Drifts for fixed base model

As we can see from the data above, the fixed model structure has a sufficient strength capacity but lateral drifts exceed the limit imposed by Romanian seismic code for existing buildings. Stiffness should be increased if a classical retrofitting solution is applied, but the price of degradation in beams in columns due to post elastic deformation remains. Time history response shows great peak accelerations for a long period of time (more than 10 seconds) which leads to important post elastic demands for members which exhibit such behavior.

Isolated base building

Linear rubber bearings were considered. Their detailing was made according to ISO 22762 "Elastomeric seismic protection isolators"[3]. Considering a target period of 3.5 seconds, the solution found, which satisfies all the requirements in the ISO code was to place a 600 mm diameter isolator under each column (35 bearings for the structure). Vertical stiffness K_v of isolators was found to be 738300 kN/m, horizontal stiffness K_h 428.399 kN/m, shape factor S1=25, shape factor S2=3,03. Horizontal displacement capacity for the maximum axial load in column is 38,43 cm and horizontal force capacity is 208,44 kN/m[4]. Analyzes were run for the seismic isolated structure and results are shown in Table 3 as well as in Fig 8 and Fig 9 a) and b).

Table 2 – Results for isolated base model – no additional damping

	Period (sec)	**Top acceleration(m/s^2)**	**Post elastic response**
Transversal direction	3,55	1,64	Small incursions into post elastic domain for lower beams
Longitudinal direction	3,64	1,36	

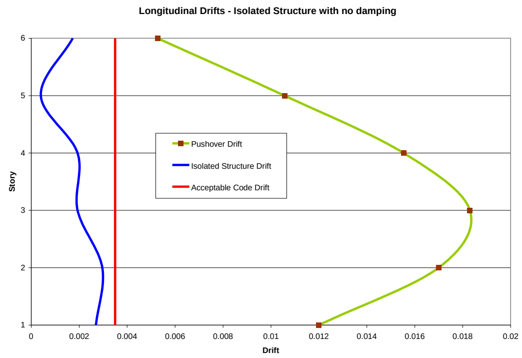


Fig 8 - Comparative story drifts for base isolated structure

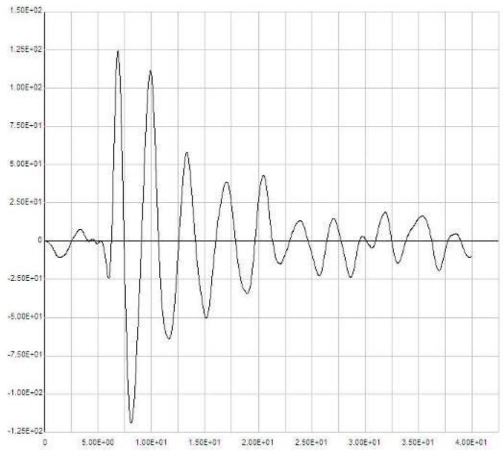


Fig 9 a) Force in isolators

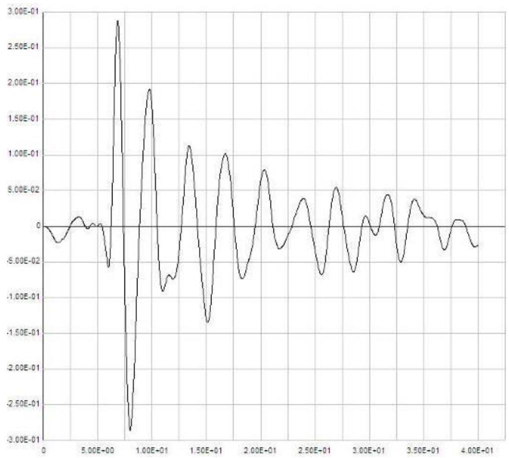


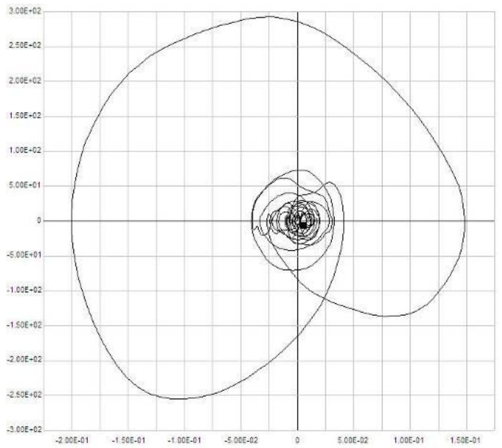
Fig 9 b) Horizontal displacement in isolators

Isolated base building with passive damping

Comparatively with fixed base model, one can observe the significant reduction in roof accelerations (even de-amplification effect since peak ground acceleration for 1977 Vrancea ground motion is 1.94 m/s^2) and a reduction in post elastic behavior of members. Drifts are significant decreased to a low value comparing the fixed base and even the code requirements. However large displacements are recorded at base level (around 35 cm). In order to decrease these effects additional passive and semi-active dampers were considered. By considering the optimal damping level studied on simplified models a 35% fraction of critical damping was considered . This means 10 dampers on each direction with a passive constant damping coefficient for each of 500 kg s/m. Results for passive damping analyzes are given in Table 4, Fig. 10 a) and b).

Table 4 – Results for isolated base model – 35% additional passive damping

	Period (sec)	Top acceleration(m/s^2)	Post elastic response
Transversal direction	3,33	1,47	All superstructure remains in elastic range
Longitudinal direction	3,41	1,29	



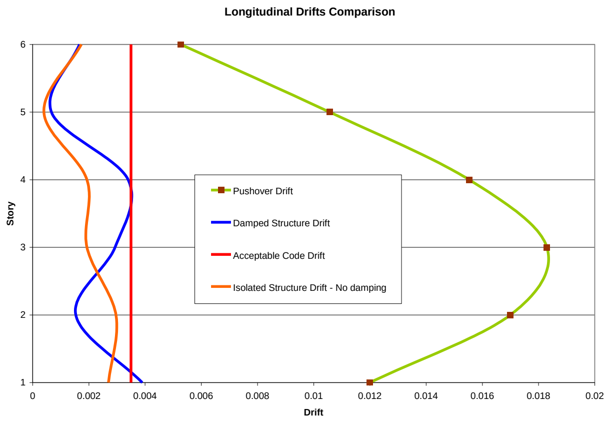


Fig 10 a) Time history plot for a passive damper Fig 10 b) Comparison of drifts

Maximum force in one passive damper reaches around 300 kN, while horizontal base displacement does not exceed 20 cm, which is considered to be an acceptable value. The roof acceleration is further decreased and the superstructure remains entirely on elastic range.

Isolated base building with semi-active dampers

Semi-active dampers are placed instead the passive dampers. Their purpose is to limit the horizontal forces into dampers by providing low damping at high velocity demands and passive (increased) damping for low velocity demands, with further benefits for the superstructure itself as it will be shown below [5]. Constitutive law for semi-active dampers is presented on Fig 11)

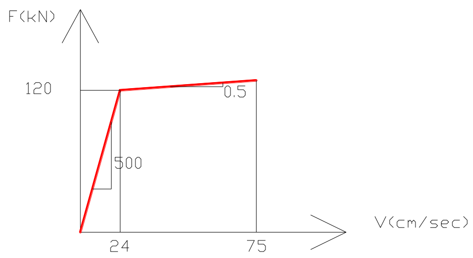


Fig 11) Force-velocity constitutive law for semi-active damper

Analyses were run for the structure with semi-active dampers and the comparatively results with the passive damped structure are synthesized on table 5.

Table 5 – Passive vs. Semi-Active Damping

	Passive	Semi-Active
Base Displacement (cm)	19,00	22,00
Roof Acceleration(m/s^2)	1,47	1,40
Force in dampers	294	120
Base maximum velocity (cm/sec)	59	75

Forces in damper are greatly reduced for the semi-active damping solution with a negligible difference on base displacement and roof acceleration. However, the base velocity is increased for the semi-active model.

Energy balance

Total amount of input energy was computed for all the cases run and presented on fig 12). It can be observed that in case of fixed base structure a great amount of energy is consumed by post elastic deformations of the members (red area on fig 12 a)), while in case of either passive or semi-active damped structure with isolated base all these energy is consumed by the dampers leaving the structure unharmed after the earthquake (purple areas of Fig 12 c and d)).

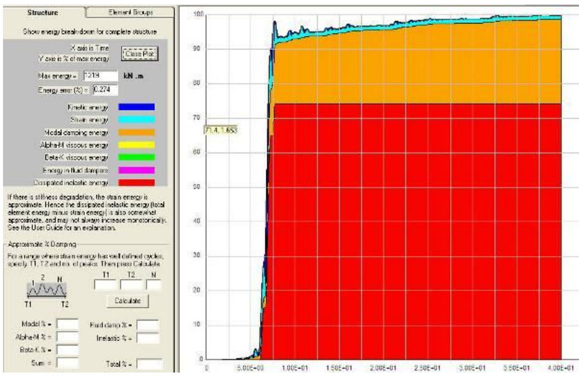


Fig 12 a) Fixed base model

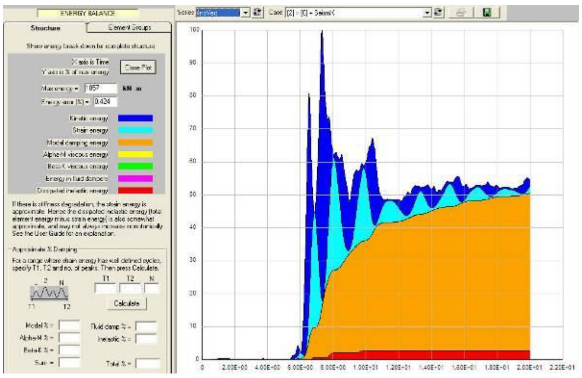


Fig 12 b) Isolated structure – no damping

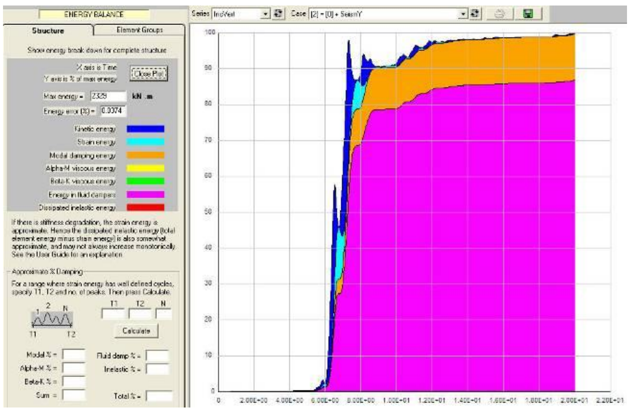


Fig 12 c) Passive damping

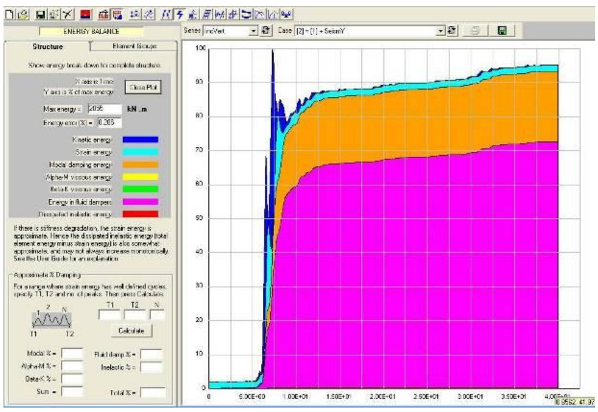


Fig 12 d) Semi-active damping

CONCLUSIONS

Simplified 2 degrees of freedom models give acceptable results and they can be used in preliminary design. Base isolation system provides low lateral displacements and drifts while the additional damping located at base level reduces the base horizontal displacement by 43% for this case. Using the semi-active control leads to lower forces into dampers with practically no significant change into structure response parameters as roof acceleration or base displacement. These systems have no damage after an earthquake so functionality of building can be never stopped and the costs of post seismic rehabilitation are virtually inexistent. One semi-active device similar to the one used in calculation was entirely produced in Romania and is currently under testing at the Technical University of Civil Engineering Bucharest.

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