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VIRTUAL ASSESSMENT OF THE EFFICIENCY OF SEISMIC PROTECTION SYSTEMS

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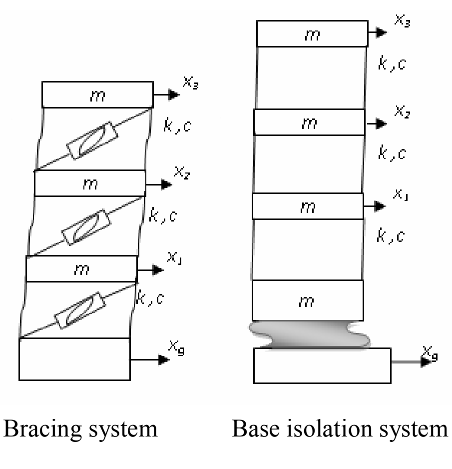
Abstract: *The efficiency of seismic protection is analyzed by using differential models of Bouc-Wen type to portray the hysteretic behaviour of devices used for both base isolation and bracing systems. Analytical methods assisted by Genetic Algorithms are developed for fitting the mathematical models to laboratory experimental data. The seismic response of structures is studied for various configurations of earthquake protection systems by using Matlab-Simulink software. The seismic inputs are either records of ground motion acceleration or synthetic accelerograms compatible with imposed design spectra. The time histories of seismic response can be visualized in real time on multi-channels virtual oscilloscopes. Through this virtual analysis, the seismic protection system can be optimally configured as to accomplish both the building structural safety and minimization of system implementation cost. .*
Keyword: *seismic protection, hysteretic characteristics, virtual simulation*

1. INTRODUCTION

Base isolation and dissipative bracing of buildings are modern and efficient seismic protection strategies already implemented in many countries. While base isolation is a more appealing solution in the case of new buildings, the dissipative braces are use especially in the seismic retrofitting of the existing ones.
The force–displacement characteristic of most seismic protection devices is of hysteretic type. Usually, the experimental hysteretic loops are obtained by imposing cyclic relative motions between the device mounting ends on the testing rig and by recording the evolution of the developed force versus the imposed displacement. By fitting a Bouc- Wen model type to experimental data, one obtains a single non-linear first order equation which can describe the evolution of force developed by one device for almost any loading pattern (periodic, a-periodic or random). All these equations are then added to the system of equations which models the motion of the protected building. Thus, is obtained an enlarged system, which can portray the dynamic behavior of the protected structure with a better accuracy than it can be achieved by employing other methods (equivalent linearization, phase description of hysteretic loops by piece-wise continuous functions, etc).
By using Matlab-Simulink software, the seismic response of this enlarged system can be visualized in real time, thus enabling a direct assessment of the employed building protection system. The earthquake buildings protection is achieved if the inter-story drift is below to 0.5%*h* (where *h* is the storey height) while keeping lateral accelerations below 0.5g.
The effect of changing the number or the type of devices used for seismic protection can be directly evaluated by inspection of the output time histories displayed on virtual oscilloscope screens. Therefore, through this virtual analysis, the seismic protection system can be optimally configured as to accomplish both the building structural safety and minimization of system implementation cost.
In this paper, the seismic behaviour of a building with three stories is investigated using a synthetic time history of the ground motion acceleration, compatible with a given design response spectrum [1]. Only lateral motion is considered, the building being treated as a shear structure. The mass of each story of the structure is considered to be concentrated at the level of the slab. These concentrated masses are connected by linear springs and viscous dampers to represent structural stiffness and damping for displacements in the elastic region. We assume that the mass, stiffness and damping distributions are uniform. The mechanical model is a MDOF system as shown in figure



Bracing system Base isolation system

Figure1: Mechanical models of protected structures

1 for the two case studies analysed in this work: structure protected by a bracing system with buckling-restrained axial dampers and by a base isolation system with elastomeric bearings. In order to assess the efficiency of considered seismic protection systems in terms of maximum admissible inter-storey drift, the storey height is assumed to be *h*=3 m.

2. ANALYTICAL MODEL

Let us consider an experimental hysteretic plot $F(y)$ obtained from the time histories of the cyclic imposed displacement $y(t)$ and of the force $F(t)$ developed by the tested seismic protection device. Next, are defined the following corresponding dimensionless time histories

$$\xi(t)=\frac{y(t)}{y_u},\varPhi(t)=\frac{F(t)}{F_u} \tag{1}$$

where y_u and F_u are reference values chosen from the experimental hysteretic plots such that to closely cover the maximum allowable range of imposed displacement and developed force, i.e. $\xi_m=\max\left|\xi(t)\right|\cong 1$, $\varPhi_{\mathrm{m}}=\max\left|\varPhi(\xi)\right|\cong 1$. For simplicity, the dimensionless parameters will be given the same names as their physical counterparts. The Bouc-Wen model of hysteretic restoring force has the following form (see for example [1]):

$$\begin{aligned}&\varPhi(t)=\alpha\xi(t)+(1-\alpha)z(t)\\&\dot{z}(t)=\left[A-\left|z(t)\right|^{p}\left(\beta+\gamma\,\mathrm{sgn}\left(z(t)\dot{\xi}(t)\right)\right)\right]\dot{\xi}(t)\end{aligned} \tag{2}$$

The model parameters $\alpha\in[0,1]$, $A>0$, β, $\gamma>0$ and $p>0$ control the shape and the size of the hysteresis loop. The reason behind using the model defined by equations (2) is to enable variation of the total contribution of the non-linear restoring force to the overall force.The values of parameters A, β, γ, p must be determined such that the obtained Bouc-Wen loop represents a good approximation of the experimental data. By applying the genetic algorithms method developed in [2], the Bouc –Wen model parameters were determined for two seismic devices, manufactured by the Italian Company FIPP INDUSTRIALE:

- Lead Rubber Bearing (LRB), used for seismic protection by base isolation;
- Buckling-Restrained Axial Damper (BRAD), used for seismic protection by inter-storey dissipative bracing.

The normalized force-displacement curves, obtained from those reported by the manufacturer in the product technical notes [3],[4], and hysteretic loops predicted by the developed fitting method, are shown comparatively in figure 2. It should be mentioned that the force-displacement curve of LRB device was obtained by a shear test conducting on a column of two devices, under a static vertical load 1500KN and a cyclic imposed displacement applied at the middle. The reference values chosen from experimental curves in this case were: $x_u=50\mathrm{mm}$, $F_u=150\mathrm{kN}$. The following values of model parameters were obtained: $\alpha=0$, $A=0.504$, $\beta=-13.165$, $\gamma=13.05$, $p=0.74$. For BRAD experimental loops the reference units are: $x_u=20\mathrm{mm}$, $F_u=200\mathrm{kN}$, and figure 2 depicts the predicted and experimental loops for three different amplitudes of the imposed displacement, for the following set of model parameters $\alpha=0$, $A=4.1$, $\beta=-7.72$, $\gamma=12.07$, $p=1.054$.

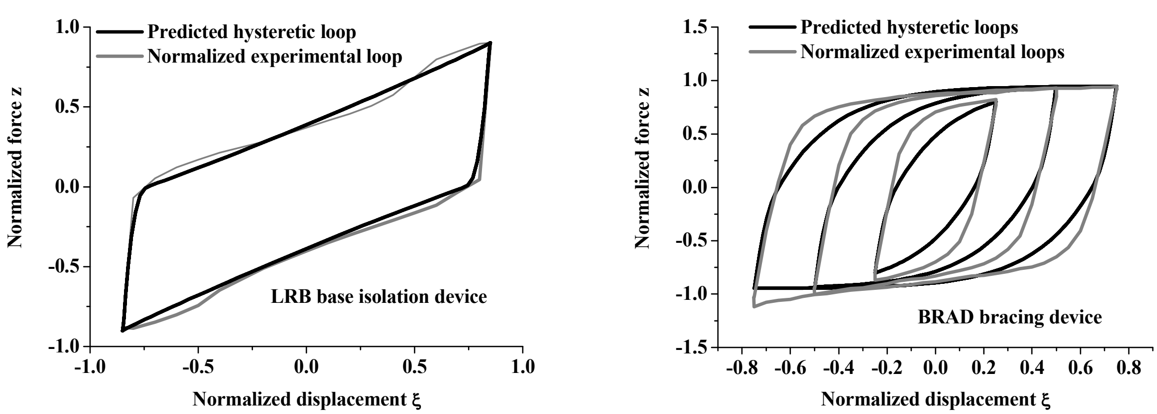


Figure 2: The experimental and predicted hysteretic loops

By using the notations shown in figure 1, the following system parameters are defined

$$\omega = \sqrt{\frac{k}{m}}, \ \varsigma = \frac{c}{2m\omega} \tag{3}$$

For a uniform three mass system, the fundamental frequency is 0.445ω. Hence given the first vibration mode frequency of a uniform building the natural frequency of the three subsystems can be deduced.
The dimensionless inter-storey relative displacements (drifts) and dimensionless ground acceleration are defined by

$$\xi_i = \frac{y_i}{y_u}, \ y_1 = x_1 - x_g, \ y_i = x_{i-1} - x_i, \ i = 2,3, \ \ddot{\eta}_g = \frac{\ddot{x}_g}{y_u} \tag{4}$$

for the unprotected structure or protected by bracing system, and by

$$\xi_i = \frac{y_i}{y_{0u}}, \ y_0 = x_0 - x_g, \ y_i = x_{i-1} - x_i, \ i = 1,2,3, \ \ddot{\eta}_{0g} = \frac{\ddot{x}_g}{y_{0u}} \tag{5}$$

for base isolated structure.
The dimensionless hysteretic forces developed seismic protection system can be expressed as

$$\begin{aligned} \Phi_i(\xi_i) &= \frac{F_i(y_i)}{F_u} = \alpha_i \frac{F_{\mathrm{BRAD}}(\xi_i y_u)}{F_u} = \alpha_i z_i(\xi_i), \ i = 1,2,3, \\ \Phi_0(\xi_0) &= \frac{F_0(y_0)}{2F_{0u}} = \alpha_0 \frac{F_{\mathrm{BIS}}(\xi_0 y_{0u})}{2F_{0u}} = 0.5\alpha_0 z_0(\xi_0) \end{aligned} \tag{6}$$

where $\alpha_i, \, i = 0,1,2,3$ are gain coefficients taking into account the number of installed devices between building levels. In case of BRAD devices these coefficients depend also on the angle of inclination with respect to the ground.
The dimensionless equations of motion, describing the seismic response of systems shown in figure 1, can be written as

$$\begin{cases} \ddot{\xi}_1 = -\omega^2\xi_1 + \omega^2\xi_2 - 2\varsigma\omega\dot{\xi}_1 + 2\varsigma\omega\dot{\xi}_2 - a_1 z_1 + a_2 z_2 - \ddot{\eta}_g \\ \ddot{\xi}_2 = \omega^2\xi_1 - 2\omega^2\xi_2 + \omega^2\xi_3 + 2\varsigma\omega\dot{\xi}_1 - 4\varsigma\omega\dot{\xi}_2 + 2\zeta\omega\dot{\xi}_3 + a_1 z_1 - 2a_2 z_2 + a_3 z_3 \\ \ddot{\xi}_3 = \omega^2\xi_2 - 2\omega^2\xi_3 + 2\varsigma\omega\dot{\xi}_2 - 4\varsigma\omega\dot{\xi}_3 + a_2 z_2 - 2a_3 z_3 \\ \dot{z}_i = \left[A - |z_i|^p\left(\beta + \gamma\,\mathrm{sgn}(z_i\dot{\xi}_i)\right)\right]\dot{\xi}_i, \ i = 1,2,3 \end{cases} \tag{7}$$

for protected structure by bracing system, and

$$\begin{cases} \ddot{\xi}_0 = \omega^2\xi_1 + 2\varsigma\omega\dot{\xi}_1 - a_0 z_0 - \ddot{\eta}_{0g} \\ \ddot{\xi}_1 = -2\omega^2\xi_1 + \omega^2\xi_2 - 4\varsigma\omega\dot{\xi}_1 + 2\zeta\omega\dot{\xi}_2 + a_0 z_0 \\ \ddot{\xi}_2 = \omega^2\xi_1 - 2\omega^2\xi_2 + \omega^2\xi_3 + 2\varsigma\omega\dot{\xi}_1 - 4\varsigma\omega\dot{\xi}_2 + 2\zeta\omega\dot{\xi}_3 \\ \ddot{\xi}_3 = \omega^2\xi_2 - 2\omega^2\xi_3 + 2\varsigma\omega\dot{\xi}_2 - 4\varsigma\omega\dot{\xi}_3 \\ \dot{z}_0 = \left[A_0 - |z_0|^{p_0}\left(\beta_0 + \gamma_0\,\mathrm{sgn}(z_0\dot{\xi}_0)\right)\right]\dot{\xi}_0 \end{cases} \tag{8}$$

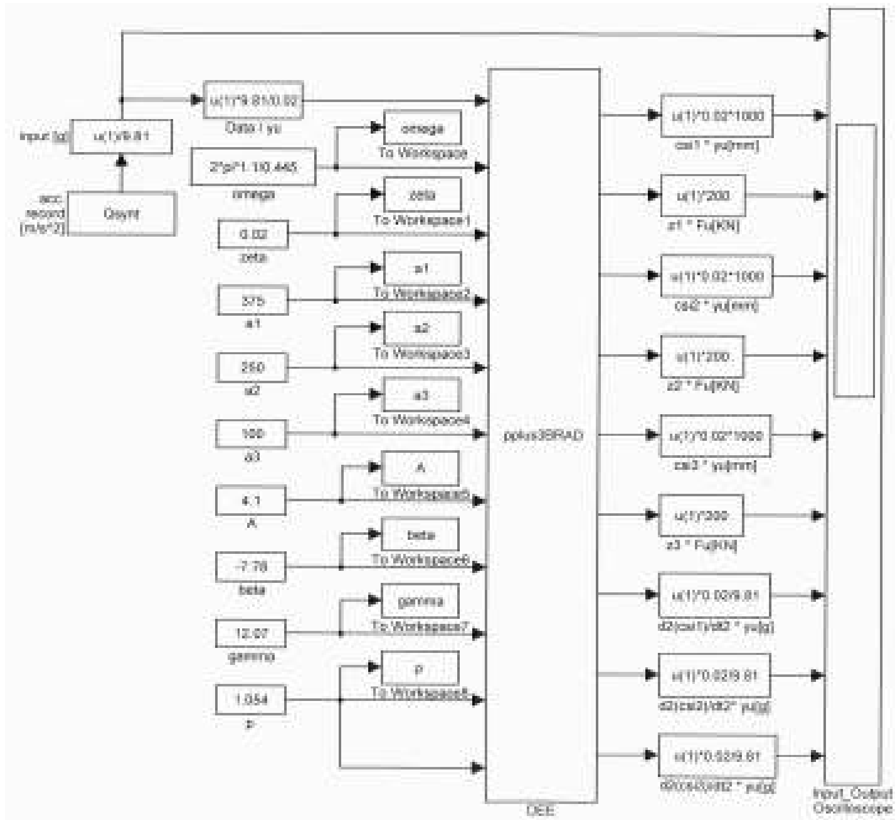
for based isolated structure. In the above equations the parameters $a_i, \, i = 0,1,2,3$ are given by

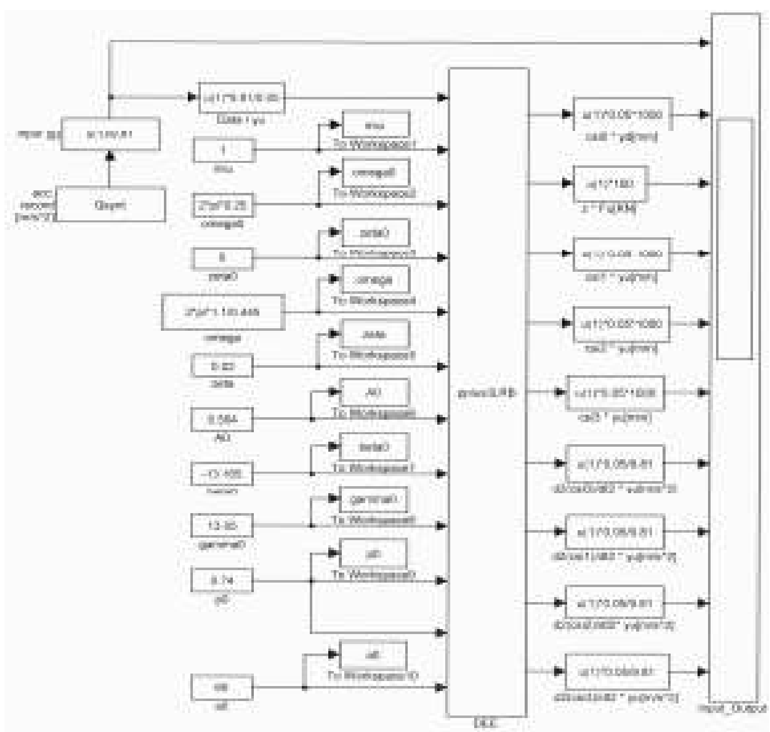
$$a_0 = \frac{0.5\alpha_0 F_{0u}}{m y_{0u}}, \ a_i = \frac{\alpha_i F_u}{m y_u}, \ i = 1,2,3 \tag{9}$$

The seismic behaviour of unprotected structure is described equations (7) for $a_i = 0, \, i = 0,1,2,3$.

3. VIRTUAL ANALYSIS OF SEISMIC PROTECTION EFFICIENCY

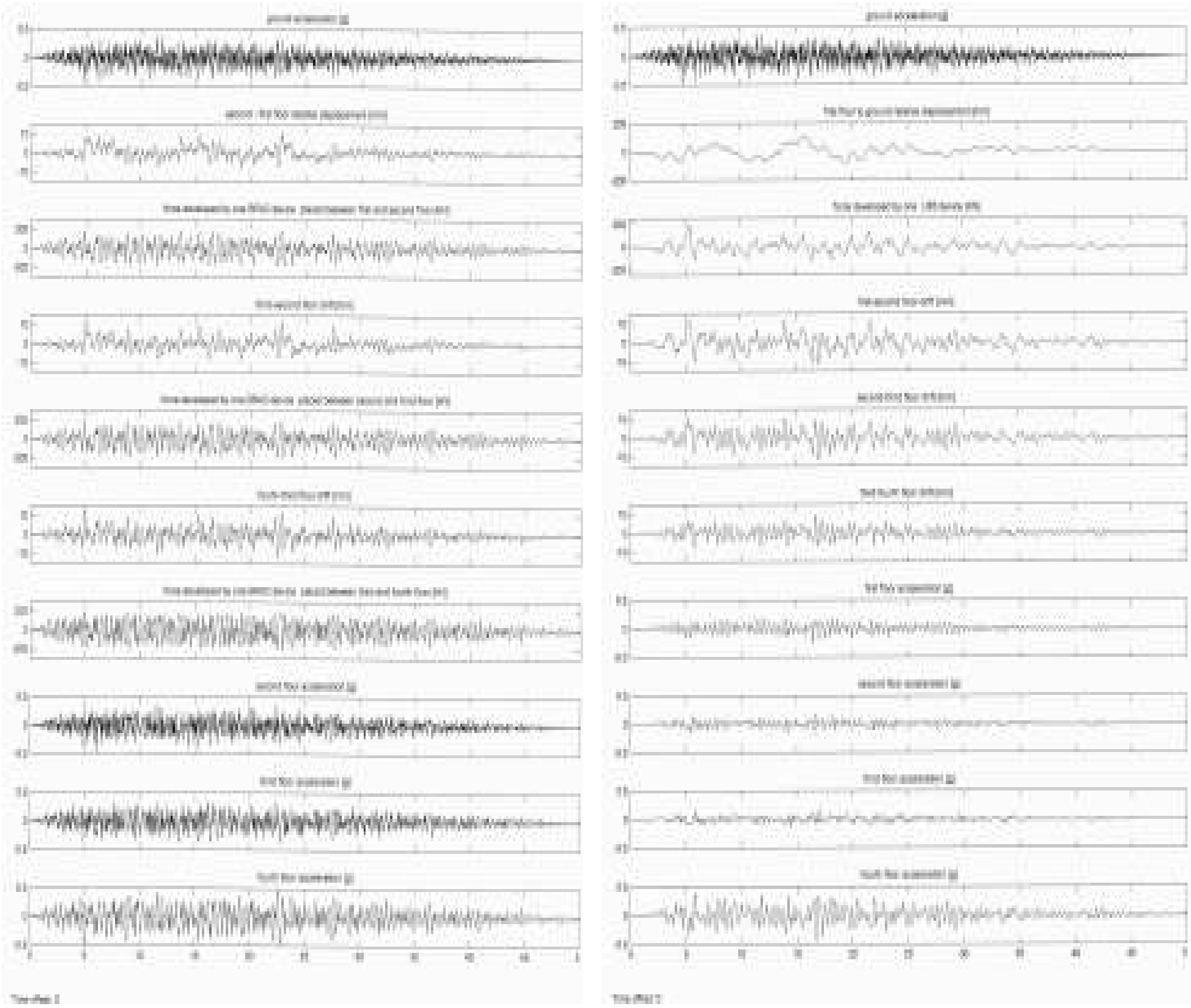
The Simulink flow charts, showing the optimum configuration of the base isolation and bracing protection systems and the input-output time histories, are presented in figures 3 and 4. The optimum configuration was obtained by a few iterative steps by modifying the values of gains $a_i = 0, \, i = 0,1,2,3$ in the corresponding parameter blocks and by visual inspection of the maximum values of the seismic output, displayed on the multi-channel oscilloscope screen. The comparison of maximum values of inter-storey drift and of the floors lateral acceleration with the above specified limits shows that both seismic protection systems can assure the building structural safety during the earthquake. It should be mentioned that the response spectrum of synthetic ground acceleration input is above the design response spectrum over the entire period range of interest from seismic point of view, as it is shown in figure 5. The value $T_1 = 0.9\mathrm{s}$ of the fundamental period of the considered structure was chosen such that to fall within the period range in which the response spectrum displays maximum values. To better evaluate the efficiency of seismic protection systems, in figure 6 is presented the seismic output of the unprotected structure. It is readily seen that the unprotected structure would be destroyed by the considered seismic motion.





Bracing system Base isolation system

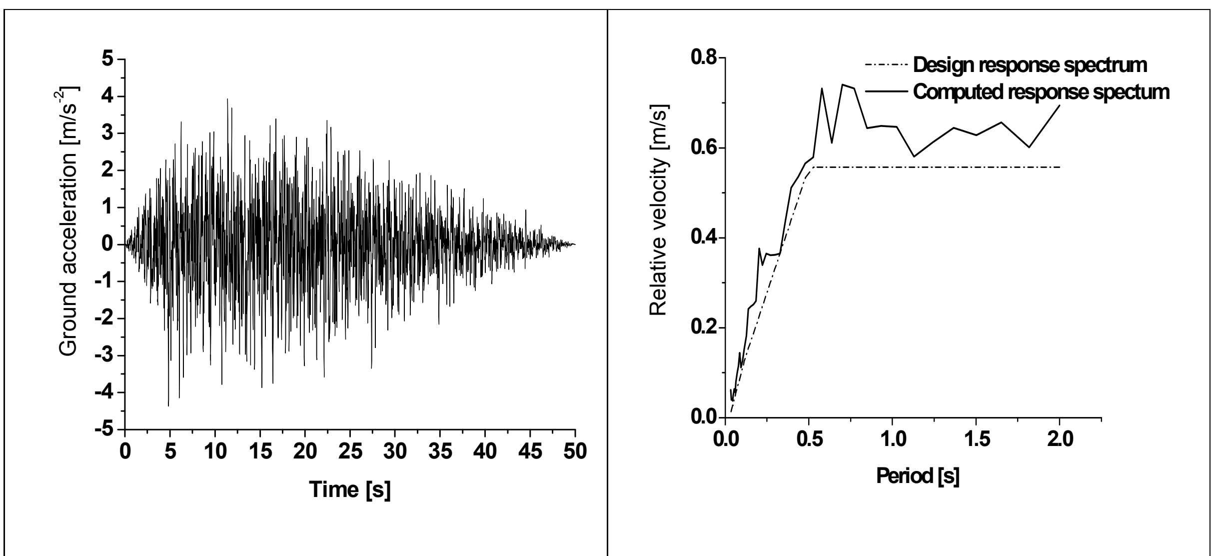
Figure 3: Simulink flowcharts



Bracing system

Base isolation system

Figure 4: Seismic response of earthquake protected structure



Synthetic time history of ground acceleration	Design and computed velocity response spectra

Figure 5: Characteristics of seismic input

4. CONCLUSION

A virtual method to assess the efficiency of seismic protection bracing and base isolation systems is presented.
The hysteretic behavior of the seismic protection devices is portrayed by differential models of Bouc-Wen type, identified from experimental data by an inverse method based on analytical relationships and genetic algorithms.
The seismic output of protected structure is analyzed by using Simulink flowcharts build such as to facilitate the modification of earthquake input or of system parameters with immediate visualization of the resulting effect on seismic protection efficiency.
Through this virtual analysis, the seismic protection system can be optimally configured as to accomplish both the building structural safety and minimization of system implementation cost by avoiding the use of a redundant number of seismic devices.
The simulation results advocate the efficiency of using passive seismic protection devices with hysteretic characteristics, which include in the same element both the elastic and the dissipative properties necessary to reduce the structural seismic response.
The base isolation systems can provide an important reduction of accelerations transmitted to the structure, such that the structural elements remain in the elastic field. This type of earthquake protection system has a low-pass filtering effect on the ground acceleration input, as one can see by comparing the seismic responses plotted in figure 3. Their use is imperious for buildings of primary importance like hospitals, public buildings, historical monuments, etc.
The bracing systems can be implemented much easier, especially for seismic retrofitting of existing buildings, in order to improve the seismic response of RC frames built without capacity design approach. The energy dissipation in the bracing devices provides an important reduction of inter-storey drift, thus reducing the damage of structural elements

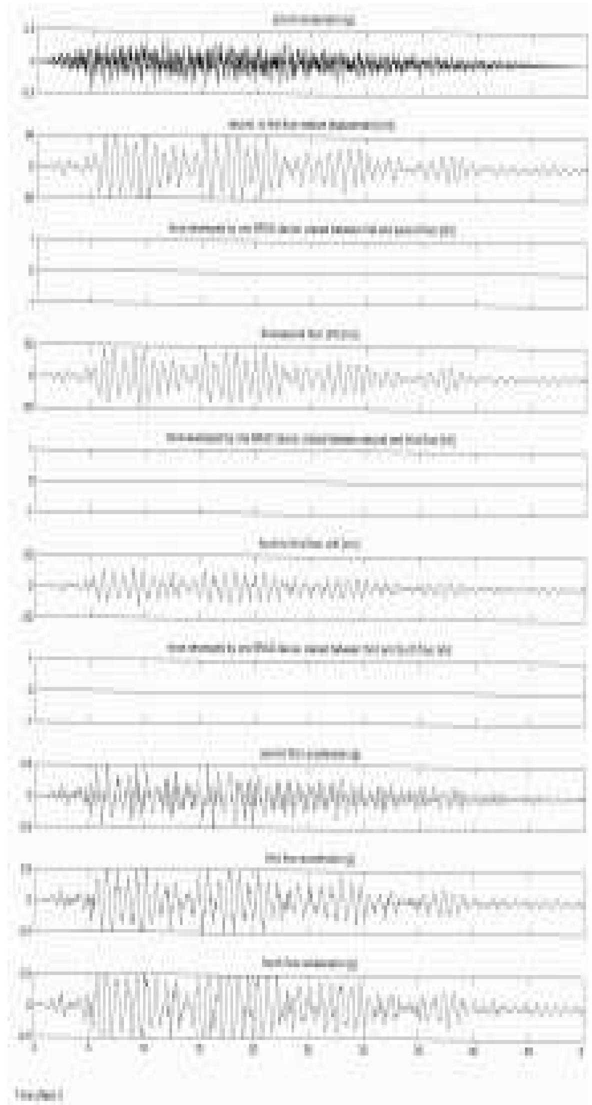


Figure 6: Seismic response of unprotected structure

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