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Ana-Maria Mitu, Tudor Sireteanu, Daniel Baldovin

On the Efficiency of a Base Isolation System

The aim of this paper is to present the analyses of the efficiency for a base isolation system. To portray the hysteretic behavior of the devices used for seismic protection the Bouc-Wen model is used. The non-linear first order equation which can describe the evolution of force developed by one device for almost any loading pattern are added to the system of equations which models the dynamical behavior of the protected building. Using Matlab-Simulink software, the model are employed to investigate the efficiency of the base isolation devices by comparing the seismic response of protected and unprotected buildings subjected to strong seismic actions.

Keywords*: hysteretic characteristics, base isolation system, Bouc-Wen model*

1. Introduction

Base isolation and dissipative bracing of buildings are modern and efficient seismic protection strategies already implemented in many countries. The force–displacement characteristic of most seismic protection devices is of hysteretic type. The Bouc-Wen model, widely used in structural and mechanical engineering, gives an analytical description of a smooth hysteretic behavior. It was introduced by Bouc [1] and extended by Wen [2], who demonstrated its versatility by producing a variety of hysteretic characteristics. The hysteretic behavior of materials, structural elements or vibration isolators is treated in a unified manner by a single nonlinear differential equation with no need to distinguish different phases of the applied loading pattern. In practice, the Bouc-Wen model is mostly used within the following inverse problem approach: given a set of experimental input–output data, how to adjust the Bouc-Wen model parameters so that the output of the model matches the experimental data. Once the hysteresis model was identified for a specific input, it should be validated for different types of inputs that can be applied on the testing rig, such as to simulate as close as possible the expected real inputs. Then this model can be used to study the dynamic behavior of different systems containing the tested structural elements or devices under different excitations 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 of devices used for seismic protection can be directly evaluated by inspection of the output time histories displayed on virtual oscilloscope screens.

In this paper the model are employed to investigate the efficiency of the base isolation devices by comparing the seismic response of protected and unprotected structures. Only lateral motion is considered, the building being treated as a shear structure.

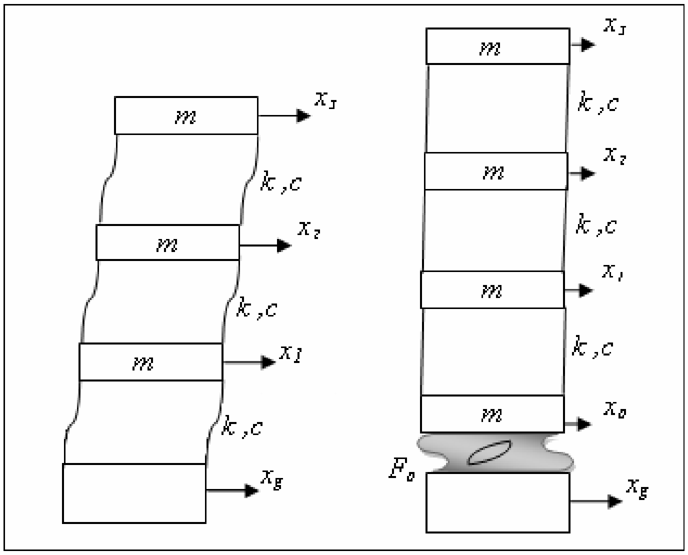

Figure 1. MDOF model of the structure

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 Fig. 1 for the two case studies analysed in this work: unprotected structure (a) versus structure protected by a base isolation system with elastomeric bearings (b).

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 models

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:

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

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. $\xi_m = \max\left|\xi(t)\right| \cong 1$, $\Phi_{\mathrm{m}} = \max\left|\Phi(\xi)\right| \cong 1$.

For simplicity, the dimensionless parameters will be given the same names as their physical counterparts. The Bouc-Wen model of dimensionless hysteretic restoring force has the following form (see for example [5]):

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

where $\alpha \in [0,1]$ and $A > 0$, β, $\gamma > 0$, $p > 0$ are the Bouc-Wen parameters, which 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 $\alpha, A, \beta, \gamma, p$ must be determined such that the obtained Bouc-Wen loop represents a good approximation of the experimental data [3]. By applying the genetic algorithms method developed in [4], were determined the Bouc –Wen model parameters for base isolation devices BIS, used for seismic protection by base isolation, manufactured by the Italian Company FIPP INDUSTRIALE. The reference values chosen from experimental curves were y_u =200 mm and F_u =1000 kN. After about 5000 generations, the following values of model parameters were obtained: $\alpha = 0$, A =0.469, β =-12.416, γ =12.236, p =1.4.

The force-displacement curves, obtained by graphically sampling the plot reported in [2] and the hysteretic predicted loop are shown comparatively in Fig. 2.

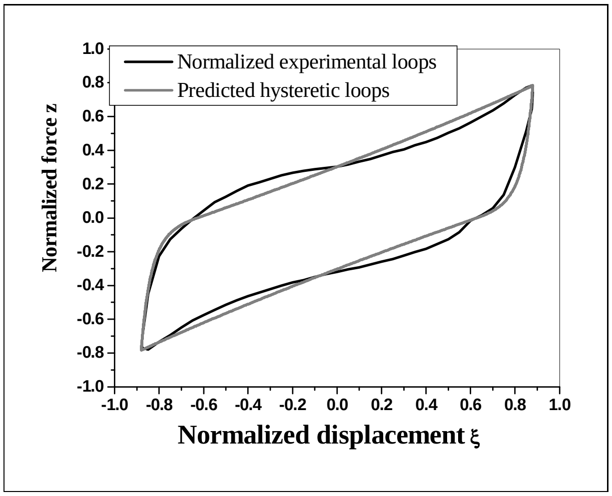

Figure 2. Experimental and predicted hysteretic loops

By using the notations shown in Fig. 1, are defined the fundamental frequency ω and damping ratio ς as follows:

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

where k denotes the spring stiffness, c represent the damping coefficient and m the mass of each story.

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

$$\xi_i = \frac{y_i}{y_\mathrm{u}}, \; y_0 = x_0 - x_\mathrm{g}, \; y_i = x_i - x_{i-1}, \; \ddot{\eta}_\mathrm{g} = \frac{\ddot{x}_g}{y_\mathrm{u}} \qquad i = 1,2,3 \tag{4}$$

The dimensionless hysteretic forces developed seismic protection system can be expressed as

$$\Phi_0(\xi_0) = \frac{F_0(y_0)}{F_\mathrm{u}} = \alpha_0 \frac{F_{\mathrm{BIS}}(\xi_0 y_{0u})}{F_u} = \alpha_0 z(\xi_0) \tag{5}$$

where α_0 is a gain coefficient taking into account the number of installed devices.

The dimensionless equations of motion, describing the seismic response of systems shown in Fig. 1, can be written as

$$\begin{cases} \ddot{\xi}_1 = -\omega^2 \xi_1 + \omega^2 \xi_2 - 2\varsigma\omega\dot{\xi}_1 + 2\varsigma\omega\dot{\xi}_2 - \ddot{\eta}_g \\ \ddot{\xi}_2 = \omega^2 \xi_1 - 2\omega^2 \xi_2 + \omega^2 \xi_3 + 2\varsigma\omega\dot{\xi}_1 - 4\varsigma\omega\dot{\xi}_2 + 2\zeta\omega\dot{\xi}_3 \\ \ddot{\xi}_3 = \omega^2 \xi_2 - 2\omega^2 \xi_3 + 2\varsigma\omega\dot{\xi}_2 - 4\varsigma\omega\dot{\xi}_3 \end{cases} \tag{6}$$

for unprotected structure and by

$$\begin{cases} \ddot{\xi}_0 = \omega^2 \xi_1 + 2\varsigma\omega\dot{\xi}_1 - a_0 z - \ddot{\eta}_g \\ \ddot{\xi}_1 = -2\omega^2 \xi_1 + \omega^2 \xi_2 - 4\varsigma\omega\dot{\xi}_1 + 2\zeta\omega\dot{\xi}_2 + a_0 z \\ \ddot{\xi}_2 = \omega^2 \xi_1 - 2\omega^2 \xi_2 + \omega^2 \xi_3 + 2\varsigma\omega\dot{\xi}_1 - 4\varsigma\omega\dot{\xi}_2 + 2\zeta\omega\dot{\xi}_3 \\ \ddot{\xi}_3 = \omega^2 \xi_2 - 2\omega^2 \xi_3 + 2\varsigma\omega\dot{\xi}_2 - 4\varsigma\omega\dot{\xi}_3 \\ \dot{z} = \left[A - |z|^p \left(\beta + \gamma \operatorname{sgn}(z\dot{\xi}_0) \right) \right] \dot{\xi}_0 \end{cases} \tag{7}$$

for based isolated structure.

In the above equations the parameter a_0 is given by

$$a_0 = \frac{\alpha_0 F_u}{m y_u}, \tag{8}$$

3. Analysis of seismic protection efficiency

In this section are shown the results illustrating the modification of dynamic behaviour of buildings subjected to strong seismic actions. The time history of the ground motion acceleration was chosen from the Internet available seismic records, having the following identification data:

- Origin Time: 1996/10/19 23:44;
- Latitude: 31.8; Longitude: 132.0l; Depth: 39 Km; Magnitude: 6.6;
- Station Code HRS018; Station Latitude: 34.3380; Station Longitude: 132.9094; Station Height: 2m;
- Record Time 1996/10/19 23:46:13; Sampling Frequency: 100Hz; Duration Time: 59s; Direction: E-W;
- Maximum Acceleration: 11gal.

The record was scaled for a maximum acceleration value of 0.5g. In Figs. 3 and 4 are shown the time history (over a time interval of $50s$) and response spectra of the seismic ground motion.

The value $T_1 = 0.9s$ 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, as it is shown in Fig. 4.

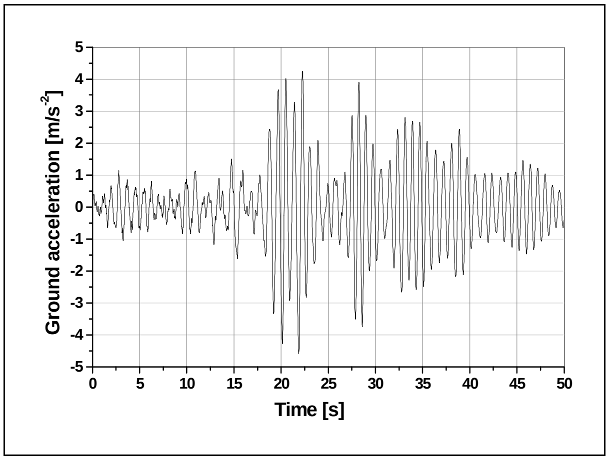

Figure 3. Time history of ground motion acceleration

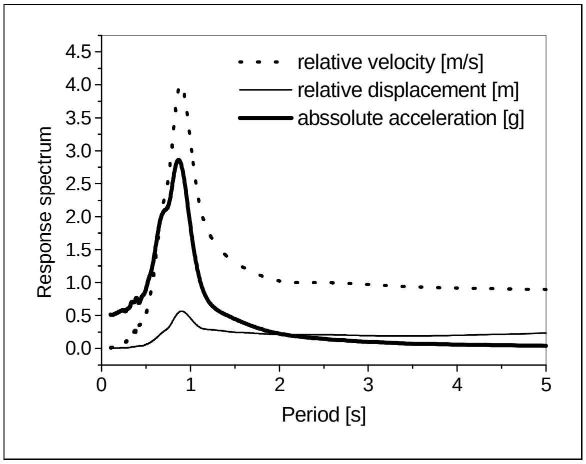

Figure 4. Response spectra of ground motion acceleration

For numerical study, the building parameters defined in Eqn (3) were given the following values: $\omega = 15.5$ rad/s, $\varsigma = 0.05$ and for the gain parameter $a_0 = 20$. The time histories of absolute acceleration $\ddot{x}_0(t)$ and of relative displacement $y_0(t)$ for base isolated structure are depicted in Fig. 5 and Fig 6 .

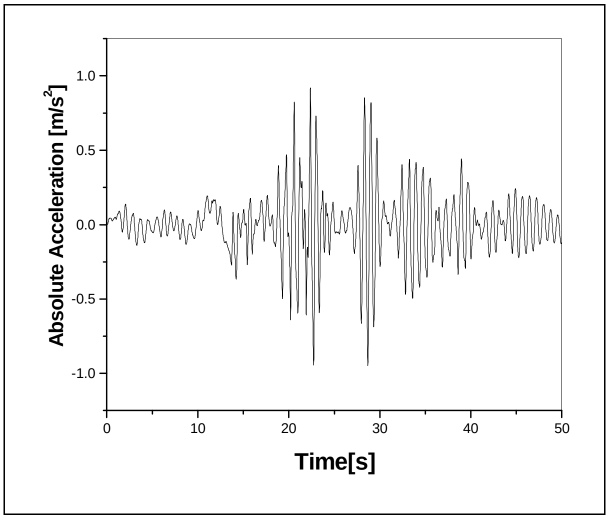

Figure 5. First floor acceleration of base isolated structure

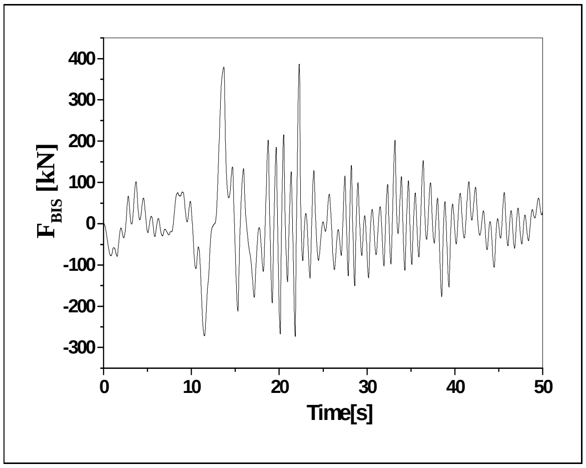

Figure 6. Relative displacement of base isolation system

In the Fig. 7 is depicted the evolution in time of the hysteretic force developed by one base isolation device and in Fig. 8 the force –displacement curve obtained during the earthquake is presented.

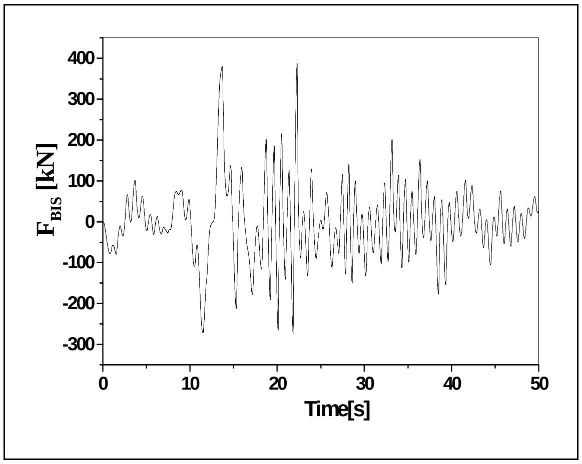

Figure 7. Force developed by one BIS device

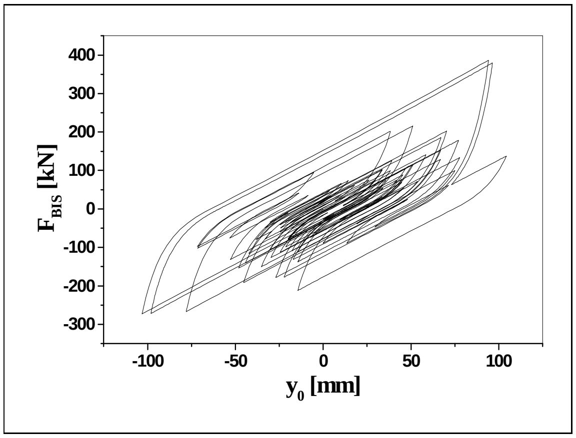

Figure 8. Hysteretic loops developed by one BIS device

The numerical simulation shows that all inter-story drifts of unprotected structure are over 0.5% from the storey height and the floors lateral accelerations are higher than admissible limits. To evaluate the efficiency of seismic protection system in Fig. 9 and Fig. 10 are presented the seismic output y_1 of the unprotected and protected structure. It is readily seen that the unprotected structure would be destroyed by the considered seismic motion. The numerical simulation shows that the seismic protection systems can assure the building structural safety during the earthquake, at least for the fundamental period used in this numerical analysis.

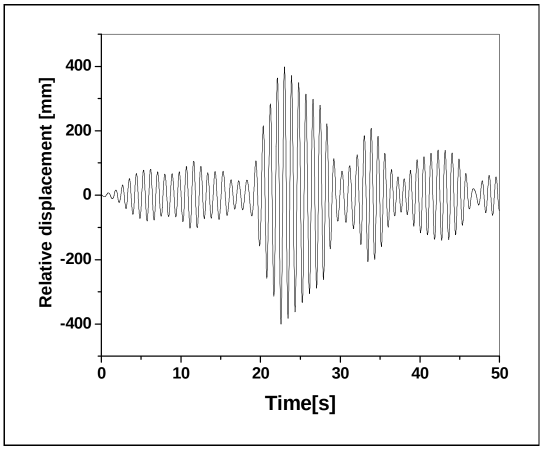

Figure 9. Relative displacement y_1 of unprotected structure

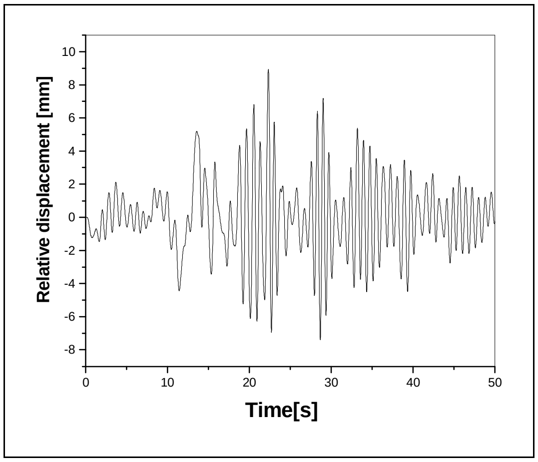

Figure 10. Relative displacement y_1 of base isolation system

4. Conclusion

To assess the efficiency of a base isolation system a virtual method 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.

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. Their use is imperious for buildings of primary importance like hospitals, public buildings and historical monuments.

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Addresses:

- Dr. Ana Maria Mitu, Institutul de Mecanica Solidelor, str. C-tin Mille, no. 15, sect 1, Bucuresti, anamariamitu@yahoo.com
- Prof. Dr. Tudor Sireteanu, Institutul de Mecanica Solidelor, str. C-tin Mille, no. 15, sect 1, Bucuresti, siretimsar@yahoo.com
- Dr. Daniel Baldovin, Institutul de Mecanica Solidelor, str. C-tin Mille, no. 15, sect 1, Bucuresti, danootzu@yahoo.com