EXPERIMENTAL AND THEORETICAL ANALYSIS OF NOVEL TELESCOPIC DEVICES FOR EARTHQUAKE PROTECTION

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Abstract. The telescopic SERB devices are compact mechanical devices designed for bracing isolation systems. These devices can provide important dissipation of the seismic energy and can generate the necessary force to prevent the building collapse for large load conditions as well as to revert the structure to the initial position. They have hysteretic properties with controlled elasticity and damping characteristics of hysteretic type. The efficiency of seismic protection is analyzed by using models to portray the hysteretic behaviour of devices used for bracing systems. Analytical methods 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 time histories of seismic response can be visualized in real time on multi-channels virtual oscilloscopes. Through virtual analysis, the seismic protection system can be optimally configured as to accomplish both the building structural safety and minimization of system implementation cost.

Key words: telescopic devices, earthquake protection, hysteretic behaviour, building seismic response, dissipative bracing.

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 an effective solution in the case of new buildings, the dissipative braces are more appealing in the seismic retrofitting of the existing ones.

The force–displacement characteristic of 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 theoretical model to experimental data, one obtains an equation describing the evolution of force developed by one device, which are then added to the system of equations which models the motion of the protected building. Thus,

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is obtained an enlarged system, which can portray the dynamic behavior of the protected structure.

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 0.3 g.

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 five stories is investigated using the time history of a slow ground motion acceleration. Only lateral motion is considered, the building being treated as a shear structure. We assume that the mass, stiffness and damping distributions are uniform. The mechanical model is a MDOF system. 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.

Various methods where developed to identify the model parameters from the experimental data of periodic vibration tests. The most employed model for hysteretic behavior is Bouc-Wen differential model [1–4]. Due to its special design, the force developed by the considered device represents the combined effect of a nonlinear elastic force and a dry friction force. Therefore, is more convenient to fit the experimental hysteretic loops by a closed analytical relation rather than through a differential model.

In the present work, such a model is obtained by identifying the stiffness characteristic and the friction force. The developed model is used to study by numerical simulation the devices efficiency in the bracing systems for earthquake protection.

2. EXPERIMENTAL TESTS

The telescopic SERB devices are compact mechanical devices designed for bracing isolation systems (Fig. 1). These devices can provide important dissipation of the seismic energy and can generate the necessary force to prevent the building collapse for large load conditions as well as to revert the structure to the initial position. They have hysteretic properties with controlled elasticity and damping characteristics.

The experimental tests have been performed on a special testing rig (Fig. 2) capable of producing quasi-dynamical forces of up to 1,500 kN.

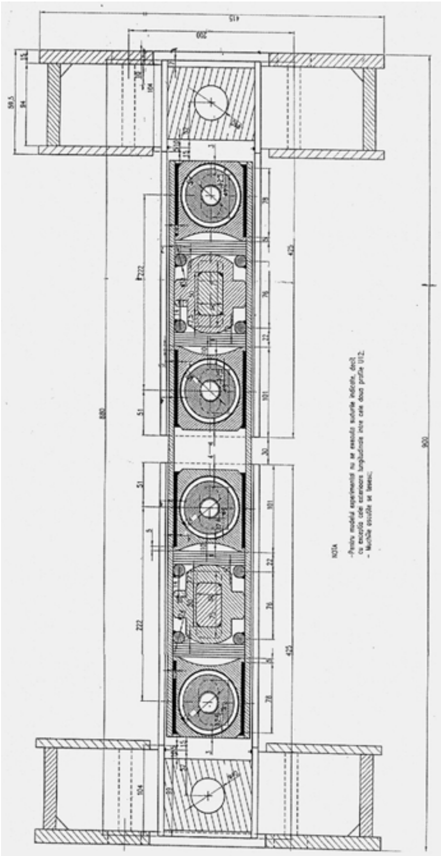


Fig. 1 – Schematic of SERB telescopic devices.

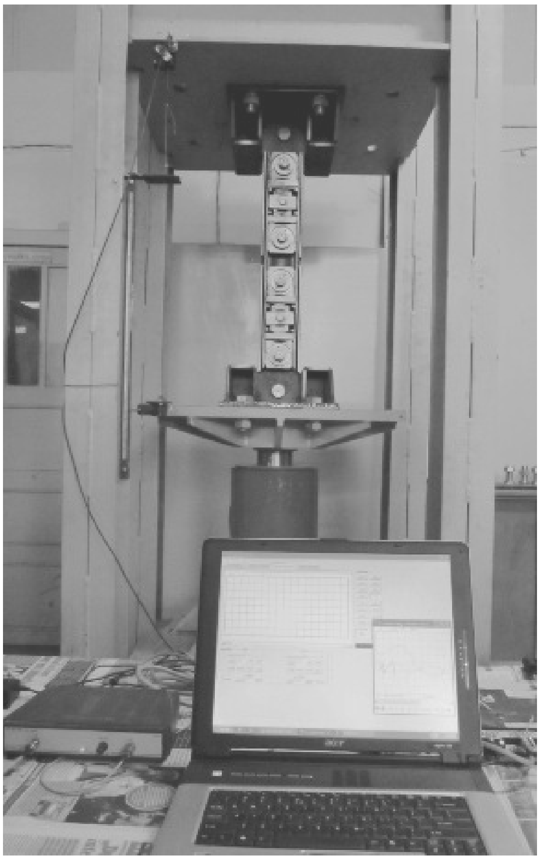


Fig. 2 – Experimental measurement of hysteretic characteristics.

The experimental tests consisted in simultaneous time histories recording of the imposed cyclic displacements and of the forces developed by the devices (Figs. 3, 4).

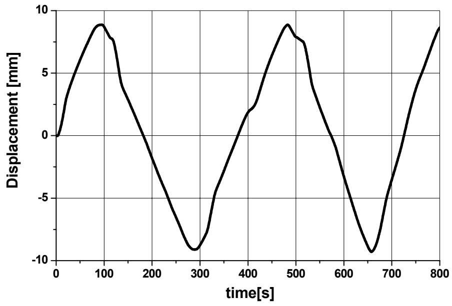


Fig. 3 – Time history of displacement.

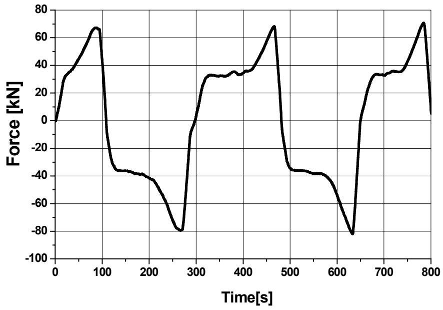


Fig. 4 – Time history of developed force.

If $y(t)$ and $F(t)$ represent the variations in time of the displacement and force signals simultaneously recorded, by removing the time variable one gets a hysteretic loop $F(y)$, which provides information concerning both the stiffness feature of the tested device and its ability to dissipate the energy of vibrations (Fig. 5).

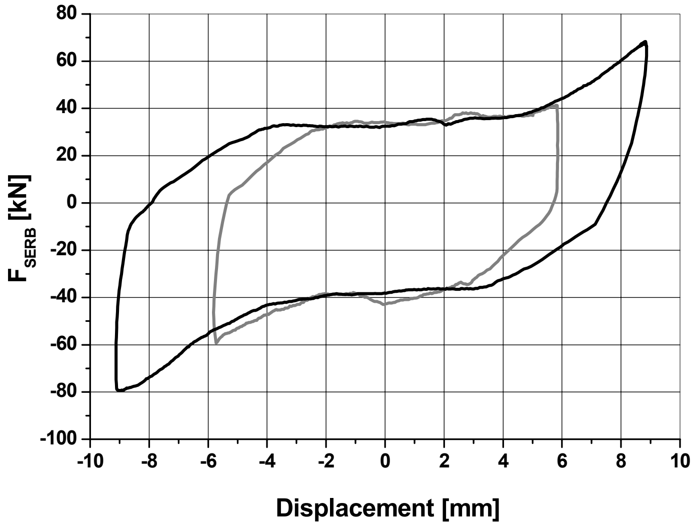


Fig. 5 – Experimental hysteretic loops.

3. 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. The following corresponding dimensionless time histories are defined:

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

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.* $\xi_m = \max|\xi(t)| < 1$, $z_{\mathrm{m}} = \max|z(t)| < 1$. For simplicity, the dimensionless parameters will be given the same names as their physical counterparts.

The experimental hysteretic characteristic of a device was analytical approximated by

$$z = a(1-\operatorname{sgn}\xi)\xi^3 + b(1+\operatorname{sgn}\xi)\xi^3 + r\tanh(\alpha\dot{\xi}) . \qquad (2)$$

The expression $a(1-\operatorname{sgn}\xi)\xi^3 + b(1+\operatorname{sgn}\xi)\xi^3$ denotes the approximated stiffness characteristic of a device with a, b parameters controlling the hysteretic shape and the term $r\tanh(\alpha\dot{\xi})$ describes the friction force. In this approach, $\tanh(\alpha\dot{\xi})$ is used for approximation of $\operatorname{sgn}\dot{\xi}$, which is present in Coulomb friction model.

In the case of SERB telescopic devices the following values of these parametres were obtained: $a = 0.25,\ b = 0.35, r = 0.36, \alpha = 0.7$.

The normalized force-displacement curves, experimentally obtained for two amplitudes of the imposed displacement on SERB device, and hysteretic loops predicted by the developed fitting method, are shown comparatively in Fig. 6.

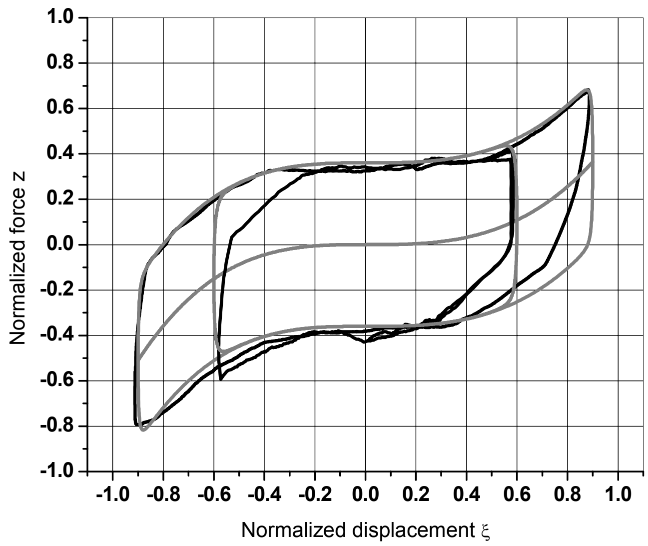


Fig. 6 – The normalized experimental (black line) and predicted (grey line) hysteretic loops for SERB devices.

The reference values chosen from experimental curves were: $y_u = 10\ \text{mm}$, $F_u = 100\ \text{kN}$.

4. APPLICATION TO CONTROL OF BUILDING SEISMIC RESPONSE

In this section the seismic behaviour of a building with five stories is investigated using the time history of the ground motion acceleration from 1977

Vrancea earthquake. 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 analytical model is a MDOF system as shown in Fig. 7 for the unprotected structure and protected structure bracing system with the considered telescopic dampers.

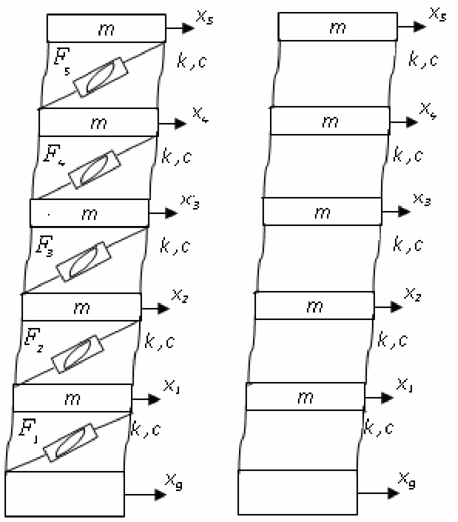


Fig. 7 – Mechanical model of protected structures vs. unprotected structure.

By using the notations shown in Fig. 7, the following system parameters are defined:

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

The dimensionless inter-storey relative displacements (drifts) and dimensionless ground acceleration for the unprotected structure or protected by bracing system are defined by:

$$\xi_i = \frac{y_i}{y_\mathrm{u}},\ y_1 = x_1 - x_\mathrm{g},\ y_i = x_{i-1} - x_i,\ i = 2,3,4,5,\ \ddot{\eta}_\mathrm{g} = \frac{\ddot{x}_\mathrm{g}}{y_\mathrm{u}}. \tag{4}$$

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

$$\Phi_i\left(\xi_i\right)=\frac{F_i\left(y_i\right)}{F_{\mathrm{u}}}=\alpha_i\frac{F_{\mathrm{SERB}}\left(\xi_i y_u\right)}{F_u}=\alpha_i z_i\left(\xi_i\right),\ i=1,\,2,\,3,\,4,\,5\,, \tag{5}$$

where α_i, $i=1, 2, 3, 4, 5$ are gain coefficients taking into account the number and of installed devices between building levels, as well as their angle of inclination with respect to the ground.

The dimensionless equations of motion, describing the seismic response of systems shown in Fig. 7, can be written as:

$$\begin{cases}\ddot{\xi}_1=-\omega^2\xi_1+\omega^2\xi_2-2\varsigma\omega\dot{\xi}_1+2\varsigma\omega\dot{\xi}_2-\ddot{\eta}_{\mathrm{g}}\\ \ddot{\xi}_2=\omega^2\xi_1-2\omega^2\xi_2+\omega^2\xi_3+2\varsigma\omega\dot{\xi}_1-4\varsigma\omega\dot{\xi}_2+2\zeta\omega\dot{\xi}_3\\ \ddot{\xi}_3=\omega^2\xi_2-2\omega^2\xi_3+\omega^2\xi_4+2\varsigma\omega\dot{\xi}_2-4\varsigma\omega\dot{\xi}_3+2\zeta\omega\dot{\xi}_4\\ \ddot{\xi}_4=\omega^2\xi_3-2\omega^2\xi_4+\omega^2\xi_5+2\varsigma\omega\dot{\xi}_3-4\varsigma\omega\dot{\xi}_4+2\zeta\omega\dot{\xi}_5\\ \ddot{\xi}_5=\omega^2\xi_4-2\omega^2\xi_5+2\varsigma\omega\dot{\xi}_4-4\varsigma\omega\dot{\xi}_5\end{cases} \tag{6}$$

for unprotected structure, and by

$$\begin{cases}\ddot{\xi}_1=-\omega^2\xi_1+\omega^2\xi_2-2\varsigma\omega\dot{\xi}_1+2\varsigma\omega\dot{\xi}_2-\alpha_1 z_1+\alpha_2 z_2-\ddot{\eta}_{\mathrm{g}}\\ \ddot{\xi}_2=\omega^2\xi_1-2\omega^2\xi_2+\omega^2\xi_3+2\varsigma\omega\dot{\xi}_1-4\varsigma\omega\dot{\xi}_2+2\zeta\omega\dot{\xi}_3+\alpha_1 z_1-2\alpha_2 z_2+\alpha_3 z_3\\ \ddot{\xi}_3=\omega^2\xi_2-2\omega^2\xi_3+\omega^2\xi_4+2\varsigma\omega\dot{\xi}_2-4\varsigma\omega\dot{\xi}_3+2\zeta\omega\dot{\xi}_4+\alpha_2 z_2-2\alpha_3 z_3+\alpha_4 z_4\\ \ddot{\xi}_4=\omega^2\xi_3-2\omega^2\xi_4+\omega^2\xi_5+2\varsigma\omega\dot{\xi}_3-4\varsigma\omega\dot{\xi}_4+2\zeta\omega\dot{\xi}_5+\alpha_3 z_3-2\alpha_4 z_4+\alpha_5 z_5\\ \ddot{\xi}_5=\omega^2\xi_4-2\omega^2\xi_5+2\varsigma\omega\dot{\xi}_4-4\varsigma\omega\dot{\xi}_5+\alpha_4 z_4-2\alpha_5 z_5\\ z_i=r\tanh(\alpha\dot{\xi}_i)+a(1-\operatorname{sgn}\xi_i)\xi_i{}^3+b(1+\operatorname{sgn}\xi_i)\xi_i{}^3,\ i=1,2,3,4,5\end{cases}, \tag{7}$$

for protected structure by bracing system.

For an uniform five mass system, the fundamental undamped frequency of the unprotected structure is given by [4]:

$$\omega_1=0.286\omega. \tag{8}$$

Hence, given the first vibration mode frequency of a uniform building, the natural frequency of the five subsystems can be deduced.

In Figs. 8 and 9 are presented the time history and the amplitude spectrum of the ground motion acceleration, recorded on North-South direction at INCERC-Bucharest, during the 1977 Vrancea earthquake.

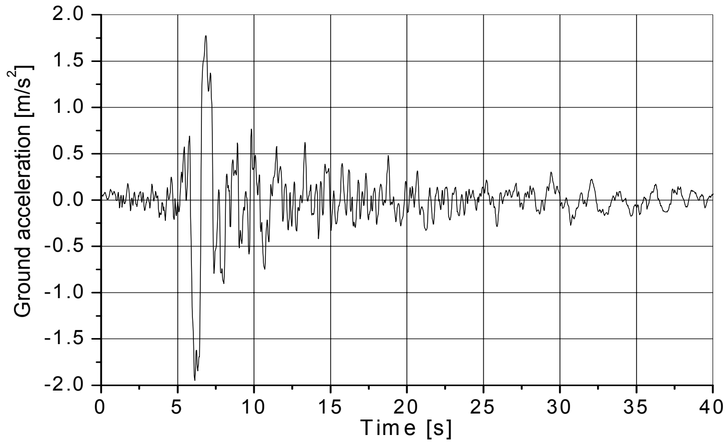


Fig. 8 – Time history of ground motion acceleration.

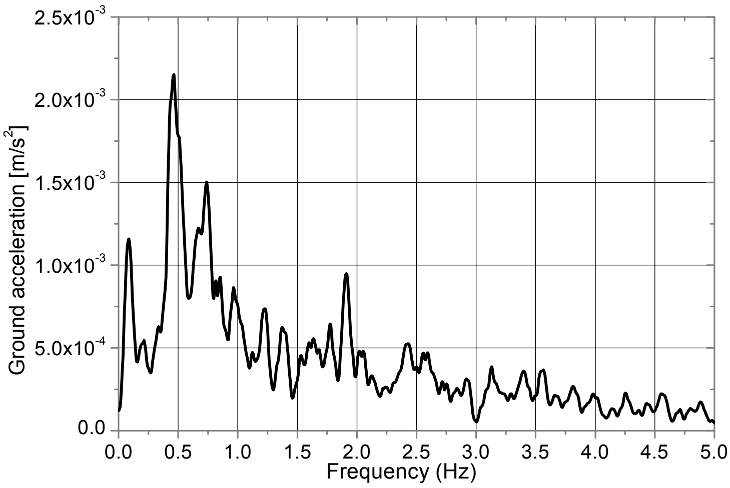


Fig. 9 – Amplitude spectrum of ground motion acceleration.

As one can see, the most important frequency components of the ground motion acceleration are placed bellow 1 Hz, *i.e.* this earthquake is of slow type. In this case, the acceptance of plastic hinges occurrence during the earthquake motion as a solution for structural anti-seismic self-protection, can “pull” the building toward the amplification range of the design response spectrum by the overall stiffness degradation effect. Therefore, by employing bracing devices with nonlinear hardening characteristics and important dissipative properties, a more reliable and efficient earthquake protection can be achieved.

The values of gain parameters α_i, $i = 1, 2, 3, 4, 5$ can be obtained by iterations so that the maximum inter-storey drift to be less than $15\,\text{mm}$, while keeping the maximum lateral acceleration as low as possible ($\ddot{x}_{\max} \cong 5\,\text{m/s}^2$).

For numerical study, the building parameters defined in (3) were given the following values: $\omega = 11, 16.5, 19.8, 22, 24.2, 26.4\ \text{rads}^{-1}$, $\varsigma = 0.05$. For the gain parameters, the following set of values were determined, such as the structural safety requirements to be fulfilled for all chosen values of building fundamental frequency: $\alpha_1 = 1{,}000$, $\alpha_2 = 1{,}100$, $\alpha_3 = 1{,}200$, $\alpha_4 = 1{,}300$, $\alpha_5 = 1{,}200$.

The maximum drift, founded in all case studies between the first and second floors, is presented in Fig. 10.

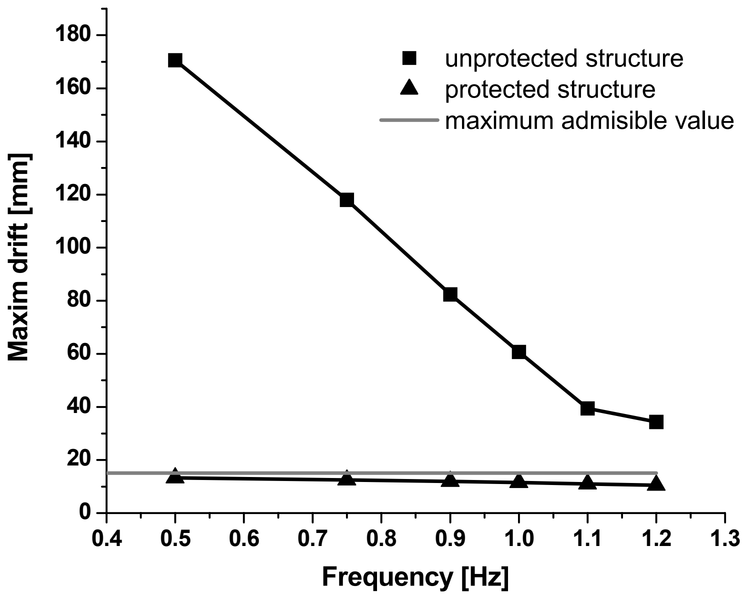


Fig. 10 – Maximum drift of unprotected and protected structure versus fundamental building frequency.

For $\omega = 19.8$ rad/s, the time histories of absolute accelerations and of relative displacements are depicted. The frequency of the building first vibration mode, obtained from (8) for this value of parameter ω, is $f_1 = 0.9\,\text{Hz}$, which falls inside the most important frequency range of the seismic input.

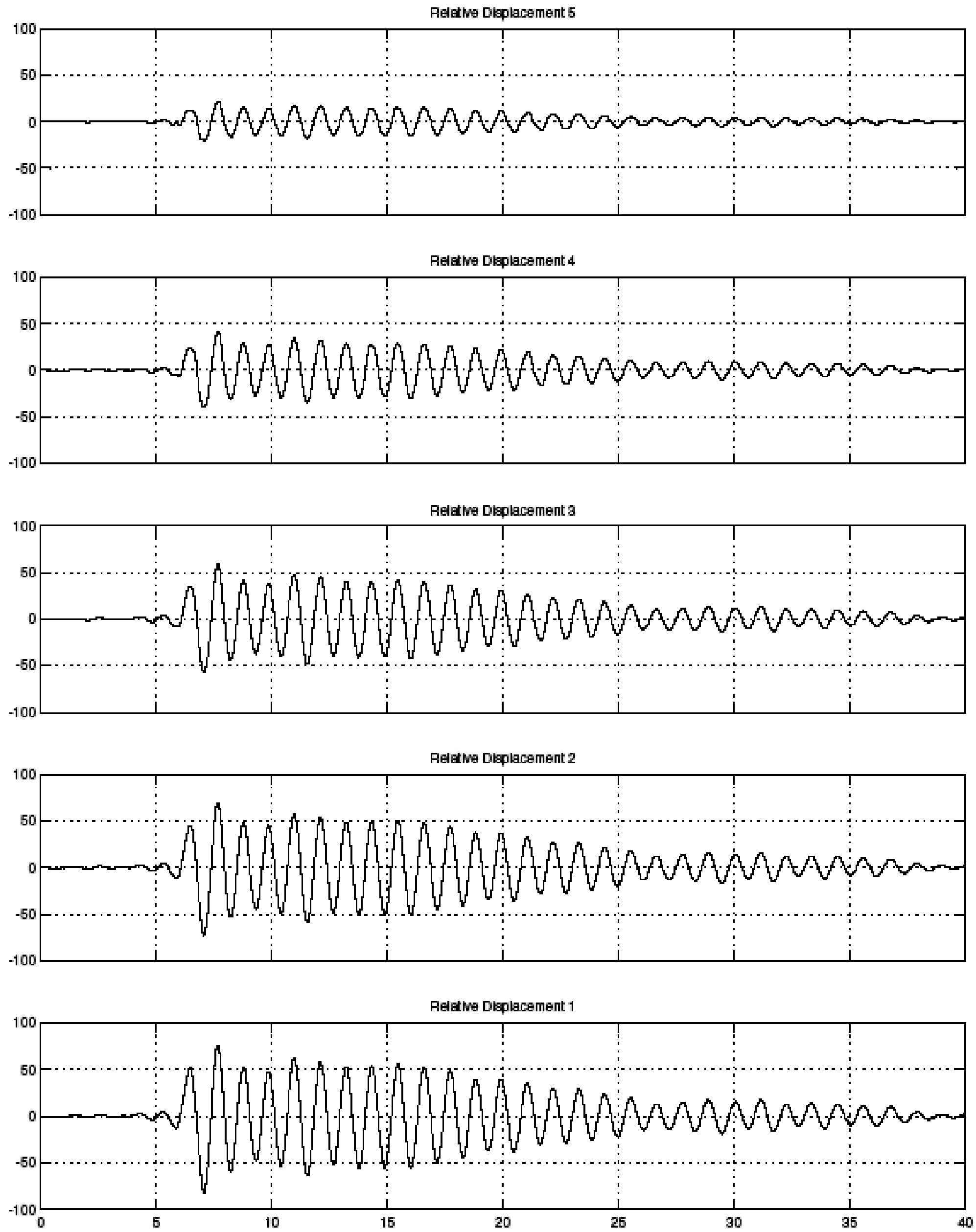


Fig. 11 – Relative displacement of unprotected structure.

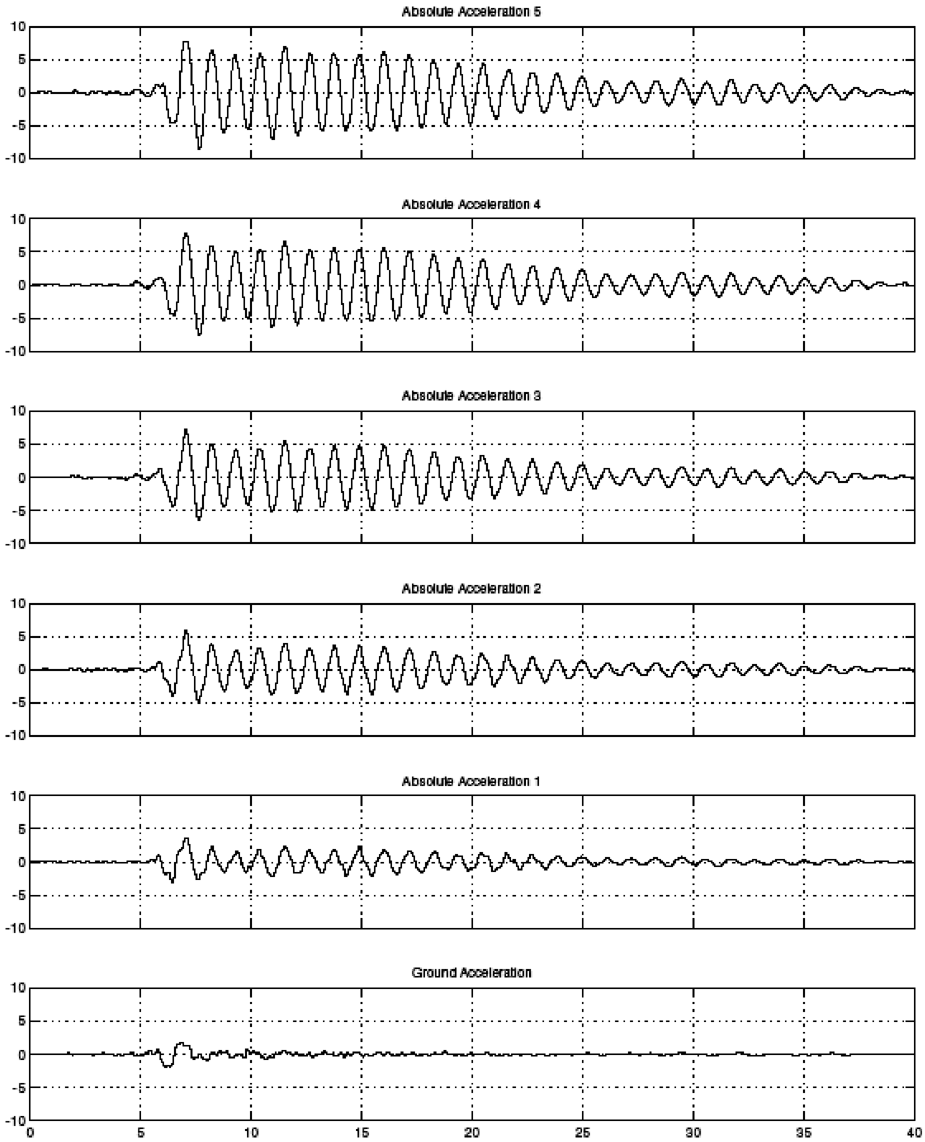


Fig. 12 – Absolute acceleration of unprotected structure.

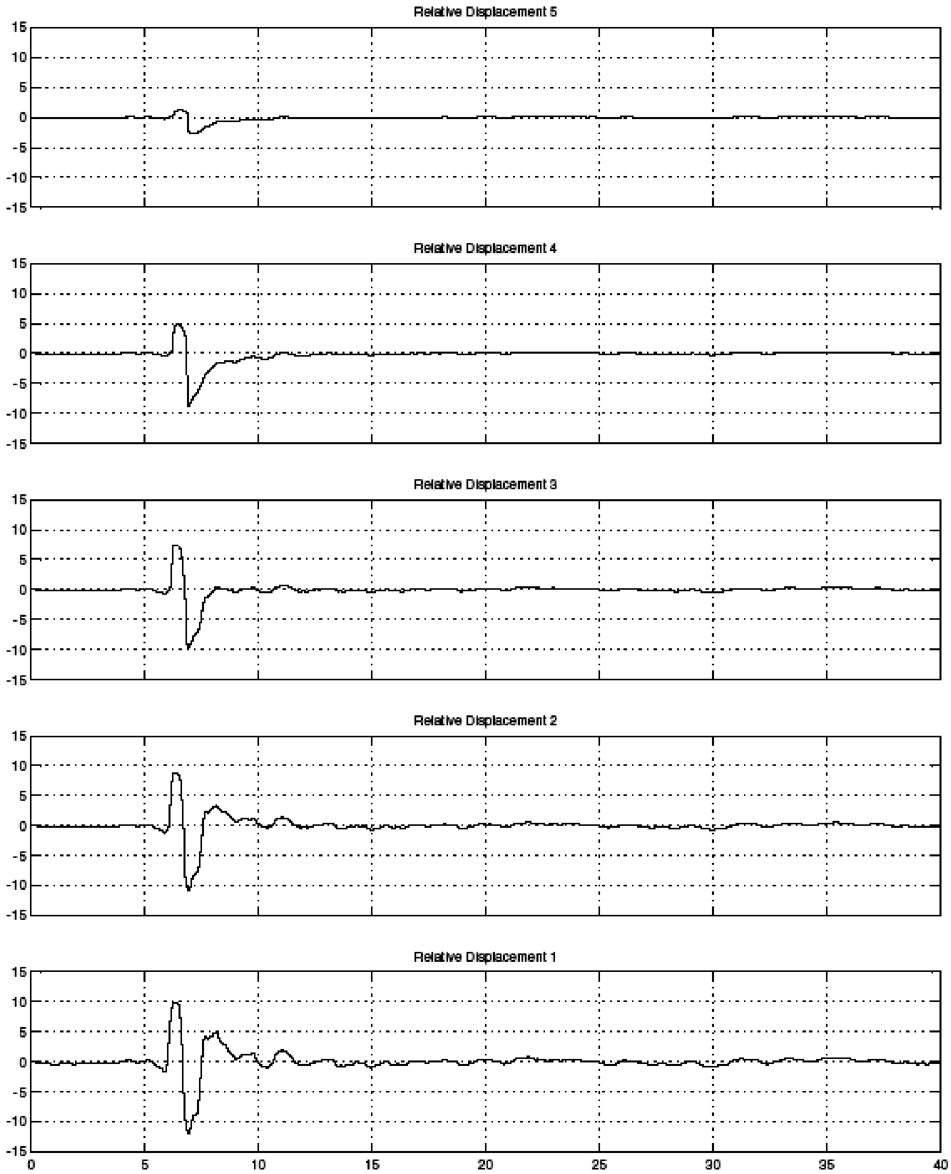


Fig. 13 – Relative displacement of protected structures.

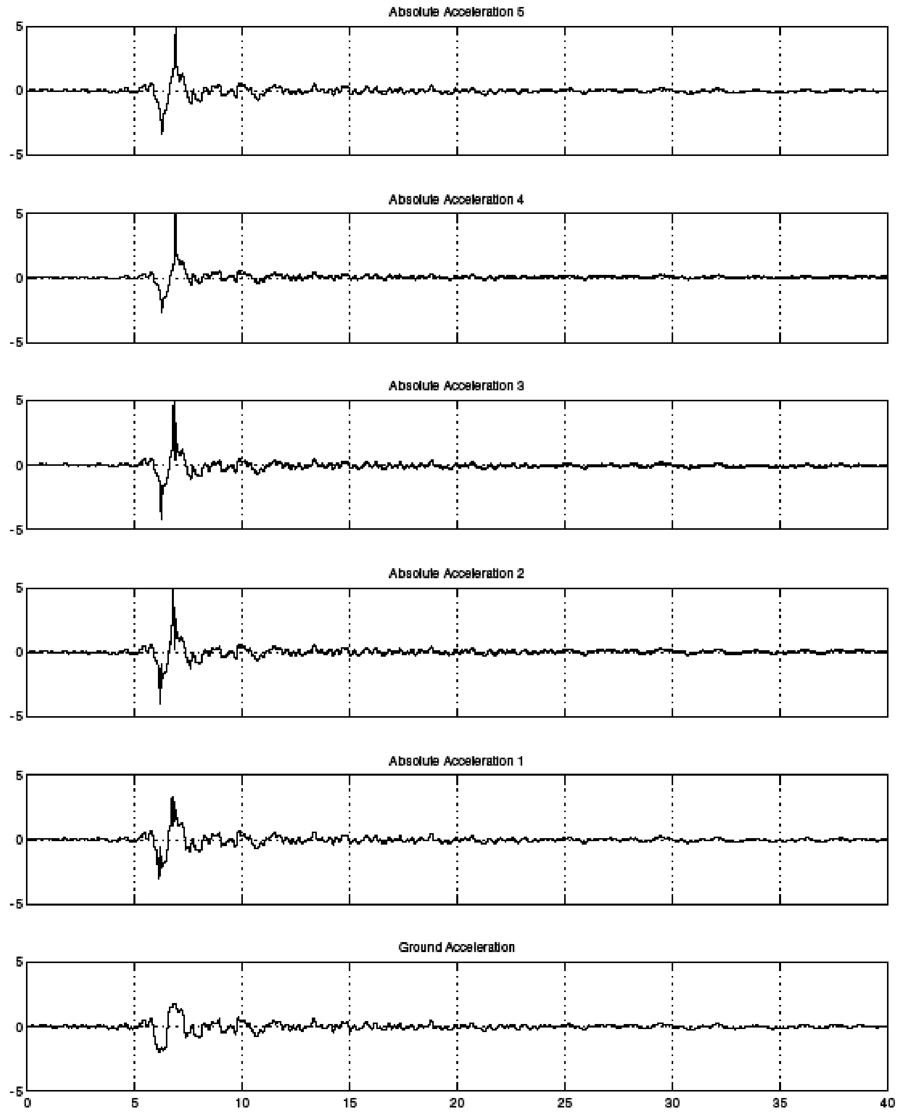
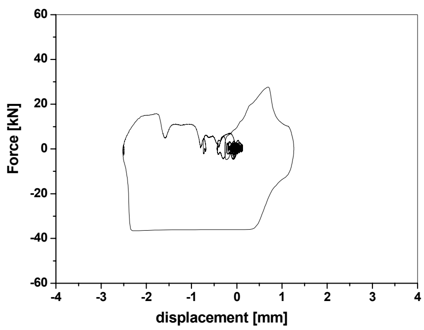
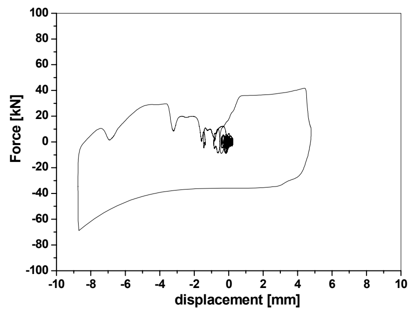


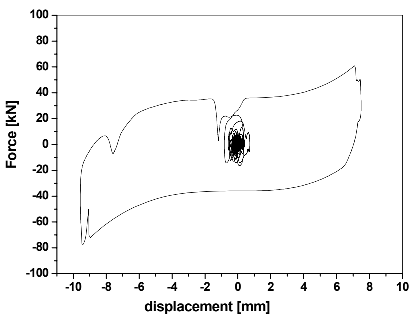
Fig. 14 – Absolute acceleration of protected structures.



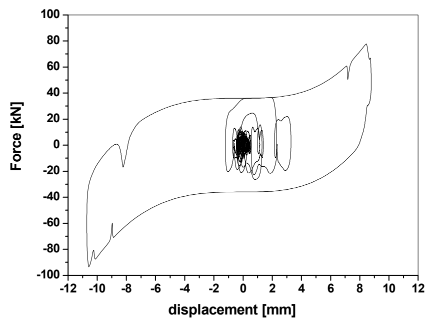
Between fourth and fifth floor



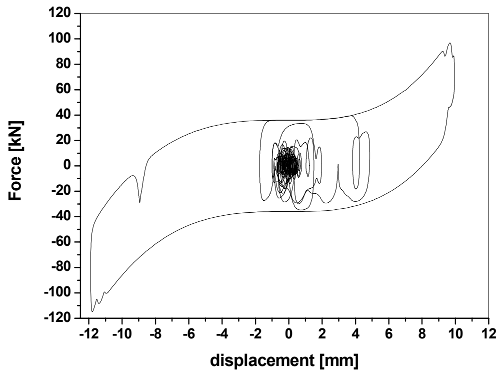
Between third and fourth floor



Between second and third floor



Between first and second floor



Between ground and first floor

Fig. 15 – Evolution of hysteretic force developed by one device SERB placed between two consecutive floors.

5. CONCLUSIONS

The telescopic SERB devices can provide important dissipation of the seismic energy and can generate the necessary force to prevent the building collapse for large load conditions, as well as to revert the structure to the initial position.

The method proposed to fit the hysteretic experimental loops is applied to portray the behaviour of SERB devices used for building seismic protection by bracing systems. The approximation of experimental data is sufficiently accurate from practical point of view.

The method efficiency is advocated by the results of its numerical application carried out to investigate the seismic behaviour of a frame structure for the unprotected and protected by considered dissipative braces. It can be notice that the self-centring capability of the considered seismic protection system is superior to buckling-restrained axial dampers (BRAD), used for seismic protection by inter-story dissipative bracing [6]. It should be pointed out also the stability of the model output during the seismic event and its practical utility for optimal configuration of earthquake protection systems.

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