BASE ISOLATION VERSUS ENERGY DISSIPATION FOR SEISMIC RETROFITTING OF EXISTING STRUCTURES

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SUMMARY

There are two alternative strategies for the seismic retrofitting of existing buildings. The first one is based on the conventional design philosophy and the second on the structural response control (active or passive). Passive control includes two families of protective systems: base isolation systems and energy dissipating systems. Base isolation is the only engineering solution that mitigates both interstory drift and high floor accelerations. The non-linear behaviour of the structure is avoided and hence the potential damages to the architectural and artistic integrity of facades and interior walls, as well as the artistic artefacts. This makes isolation a very attractive approach for seismic retrofitting of existing structures. The method is especially suitable for seismic protection of historical buildings, part of the cultural heritage of a country. The PRB (Pendulum Rubber Bearing) seismic isolation system seems to be very suitable for this aim. Some results of the experimental research developed at the Technical University of Cluj-Napoca, as well as the mathematical formulation, the effectiveness of the system and the technological solution are presented.

INTRODUCTION

The strength and conservation degradation process of architectural monuments has considerably increased during the last few years. Among the main causes of a natural and technogenic character, the following should be noted (Schwarz 1994): earthquakes of low and middle intensity lead to the accumulation of residual strain in supporting structures, the ground water level tendency existing practically on many areas, the high level of soil salinity and air pollution, the increase of seismic activity in the territory, the deterioration of systems for drainage and foundation protection due to atmospheric precipitation, the lack or insufficiency of protection zones, leakage elimination, and breakdowns of engineering networks in installations, the lack of system to control the technical state of supporting structures etc.

The last earthquakes have put into evidence the urgent character of the problem, the necessity of a radical solution. Otherwise, historical buildings, as well as existing residential ones will be definitively lost by the historical heritage of the nations.

SEISMIC RETROFITTING STRATEGIES

There are two alternative strategies that a designer may adopt when faced with retrofitting an existing building, taking into account the two aspects of earthquake engineering: demand and capacity (Buckle 1995). One is based on conventional strengthening techniques which increases the capacity of the structure to meet the likely demand. This is the most common approach. The other strategy is based on reducing the demand on the structure so that its existing capacity is sufficient to withstand the given earthquake. If we proceed from standard provisions and observe these requirements in order to create a building with a seismic resistance level which corresponds to the seismic effects of the design intensity, it is impossible to create this condition without demolishing certain parts of the structure and building up a new structure, using modern strengthening methods in order to transform the stone or brick masonry building into a R/C structure with metal inclusions. The reinforced concrete appeared to be too heavy and has led to overloading (Agostinelli 1993). The two indicator of

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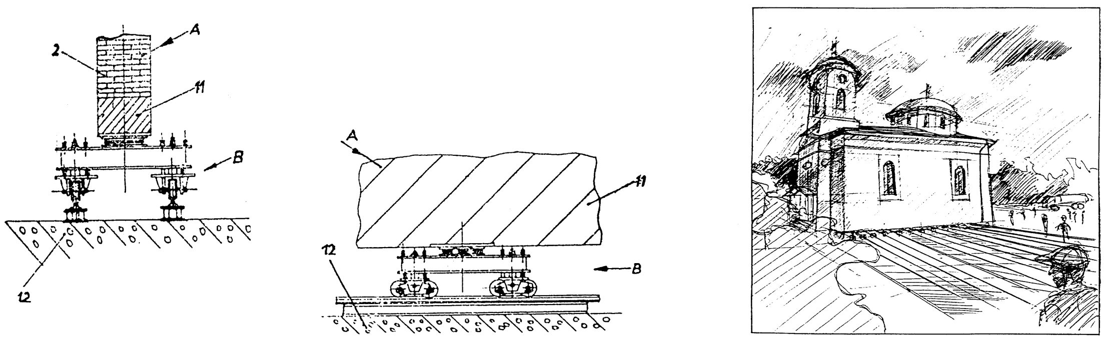
seismically-generated damage in buildings are interstory drift and floor accelerations. Interstory drift beyond certain levels will cause severe damages to non-structural components, such as partitions, ceilings, windows and may cause light fixtures to fall. High floor acceleration can cause damage to contents. The interstory drift may be reduced by using shear walls, but this leads to stiffer structure and, consequently, to higher floor accelerations. It is possible to reduce the floor accelerations by using a more flexible system, such as a moment-resisting frame, but this leads to higher interstory drifts. In conclusion, it is not possible with conventional structural systems to reduce simultaneously both interstory drift and floor accelerations. On the other hand, the use of internal energy dissipating devices is also unacceptable, due to the inherent relative displacements.

An alternative and radical approach is to reduce the demand on the structural system by using seismic isolation. Although not applicable to all structures and all site conditions, seismic isolation (or base isolation) has been shown to be a cost-effective alternative to conventional strengthening. It is the only engineering solution that mitigates both interstory drift and high floor accelerations. This approach reduces the seismic loading on the structure by interposing a flexible layer between the foundation and the building, the structure above being almost rigid. This makes isolation a very attractive approach for seismic retrofitting of existing structures. The method is especially suitable for seismic protection of historical buildings, part of the cultural heritage of a country. The building above the foundation could be repaired entirely using original materials and construction methods. In a such a way, the nonlinear behaviour of the structure is avoided and hence there are also avoided the potential damages to the architectural and artistic integrity of facades and interior walls, as well as the artistic artefacts. The base isolation solution also could completely solve other problems as: to rehabilitate the drainage system, to avoid the upraising humidity and soil salinity, the mounting of system to control the technical state of supporting structures. The PRB seismic isolation system, developed by the authors, seems to be very suitable for this aim.

THE ROMANIAN RELOCATION TECHNOLOGY ADAPTATION

The technology that has to be adapted is quite similar to the technology developed in 75-80's in Romania (Iordachescu 1973-1983), aiming at displacement of many churches and residential buildings. Unfortunately, at that time the seismic isolation system was not developed. The steps to be accomplished for realising a base isolation retrofitting of a structure have to be as follows: a - casting new longitudinal and transversal R/C girders between the old foundation beams and the unreinforced masonry walls, the latter being detached at the base from their foundation; b - construction of a R/C rigid floor above the isolation level; c - the uplifting of the entire building by means of an appropriate number of jacks; d - the mounting of the rolling tracks as well as of the moving devices (Fig. 1a, Standard 1986) and the displacement of the entire building to another temporary or



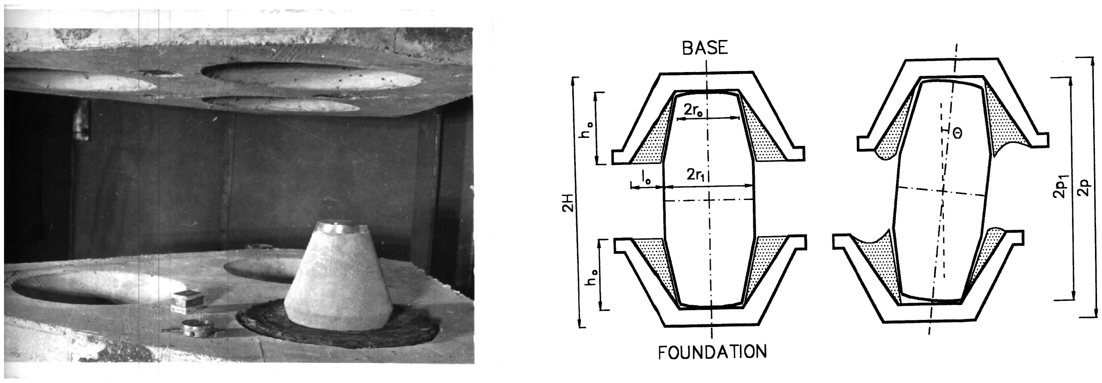
a. b. c.

Fig. 1. The relocation device, according to Standard 1986 (a, b) and the relocation of a church in Bucharest (c).

permanent site; e - the casting of the new foundation and the mounting of the base isolation system; f - making an isolation gap all around the building's perimeter in order to accommodate the design lateral displacement (an underground path may be realised to use for maintenance inspections); g - the relocation of the building to the definite site and its descent onto the base isolation bearings. Fig. 1b shows the relocation of the *Sf. Ilie Rahova* historical monument in Bucharest (Iordachescu 1986). The church (2100 t. weight) has been displaced 49 m.

THE PRB SYSTEM

The authors have proposed in previous papers the PRB base-isolation system, a kinematic-elastic system (Olariu 1982, 1992, 1994, 1998). The system consists of a series of short pendular R/C columns fixed on the top in the superstructure and at the bottom in the foundation, laterally embedded in a mass of rubber (neoprene). The columns support all the vertical loads (Fig. 2a). The pendulum units undergo rotational, horizontal and vertical



a. b.

Fig. 2. The PRB system (a) and the deflected form (b).

displacements (Fig. 2b), depending on the lateral displacement of the base, as well as on the shape of the callotes mounted at the ends of the columns. Nazin (1977) has studied different types of curves for the so-called "gravitational system" . He concluded that the best dynamical properties are given by the elliptical shape. The main dynamical quality of the elliptical shape is that as the rotation angle of the column is increased, the instantaneous vibration period becomes higher and the system is automatically taken off from the resonance position. On the other hand, the uplifting of the building weight and the eccentricity of the elliptical shaped columns provided a stability general moment (or a restoring force) that brings the structure back to its initial position after the ground motion. This is the reason why the steel callotes fixed at the ends of the columns of the PRB system are elliptically shaped.

The period of vibration of the kinematic system is independent of the supported mass of the structure and depends only on the radius of the callotes. The properties of flexibility and energy absorption capability are not interrelated. The former is entirely controlled by geometry of the callotes and the latter is controlled by the volume of the insulated rubber. This property allows the optimum design of the PRB isolation system.

THEORY AND FORMULATION

The analytical model considers that the nonlinear behaviour is concentrated at the base floor, at the PRB isolation system. The superstructure is modelled as a linear elastic shear type multi-story building with n floors, and the base-isolation system is also modelled as an additional floor with appropriate properties. The floors and the base are assumed to be infinitely rigid in plane and the centres of mass of all floors lie on a common vertical axis. The structural model and the displacement co-ordinates that will be used in formulation are shown in Fig. 3. The equations of motion for the elastic superstructure, subjected to earthquake excitation are expressed in the following form:

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} = -[M]\{I\}(\ddot{u}_g + \ddot{u}_b\}\tag{1}$$

in which $[M]$ is the diagonal superstructure mass matrix, $[C]$ is the superstructure damping matrix and $[K]$ is the superstructure stiffness matrix, respectively, of the order n x n. $\{\ddot{u}\},\{\dot{u}\}$ and $\{u\}$ represent the floor lateral displacement, velocity and acceleration vectors relative to the base, $\ddot{u}_g$ is the ground acceleration, $\ddot{u}_b$ is the base mass acceleration and $\{I\}$ is the vector of influence coefficients i.e. the vector of displacements at the centre of mass of the floors resulting from a unit translation at the centre of mass of the base. In order to solve the (n+1) unknowns, an additional equation is needed (Fig. 3). The free body dynamic equilibrium of the base floor, applying d'Alambert's principle is given by the governing equation of motion (2):

$$m_b(\ddot{u}_b + \ddot{u}_g) + F_b + F_{is} = 0 \quad (2)$$

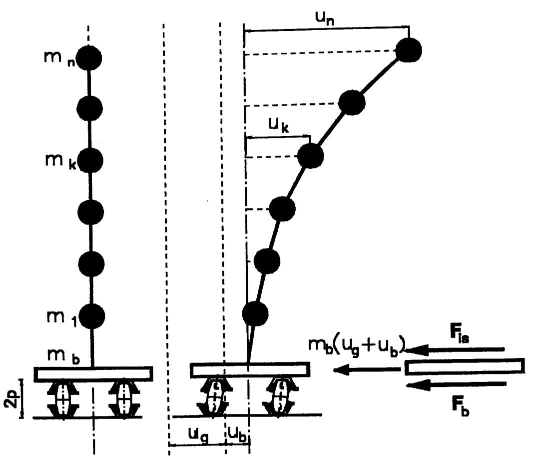


Fig. 3. The mathematical model

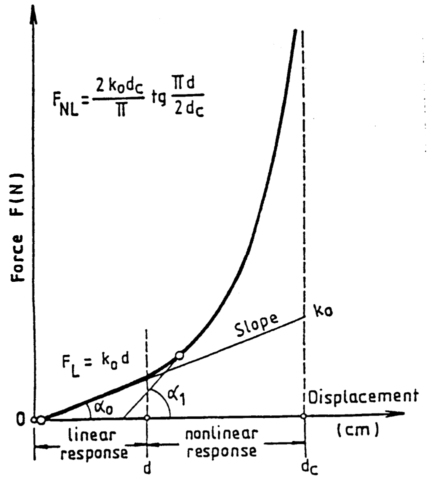


Fig. 4. The F-d function of the rubber

in which:

$$F_{is} = [M]\{\{\ddot{u}\} + \{I\}(\ddot{u}_b + \ddot{u}_g)\} \quad (3)$$

$$F_b = F_{b1} - F_{b2} - F_{b3} \quad (4)$$

where F_{is} represents the total inertia force of the superstructure and F_b the interaction force between the base floor and the PRB system. The last one includes the inertia forces of all the columns (F_{b1}), the kinematic

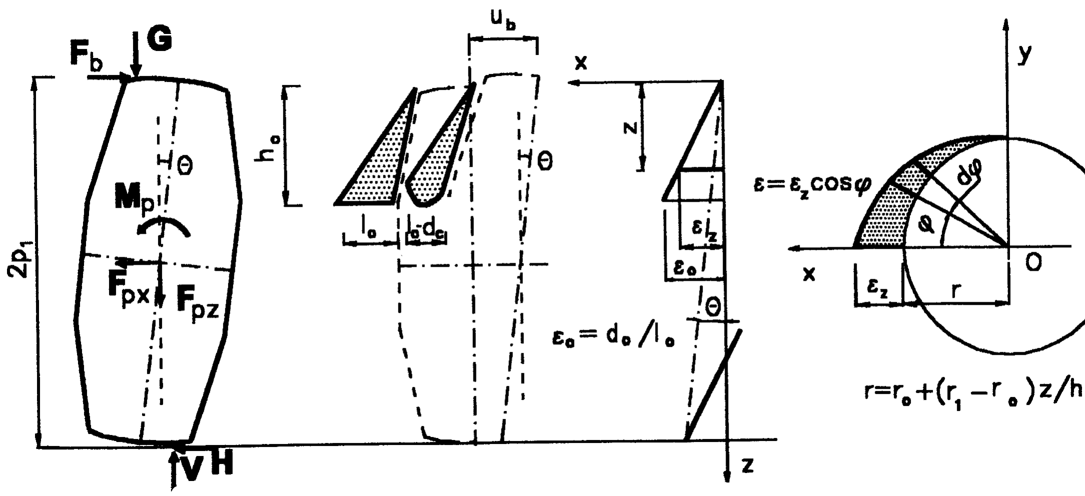


Fig. 5. The dynamic equilibrium of the pendulum unit.

restoring force caused by the weight of the structure above the isolation system acting at the eccentricity given by the column rotation (F_{b2}) and the restoring force caused by the rubber gaskets (F_{b3}). For column i the force is obtained considering the equilibrium of the column (Fig. 5):

$$F_{b1}^{i} = F_{Mp} + F_{px} + F_{pxz} \tag{5}$$

which becomes:

$$F_{b1}^{i} = \frac{J_p \cdot \ddot{\theta}_p}{2p_1} + m_p(\ddot{u}_p + \ddot{u}_g) + m_p \ddot{z}_p \frac{u_b}{4p_1} \tag{6}$$

in which m_p is the mass of column i, θ_p and $\ddot{\theta}_p$ are the rotation angle and the rotational acceleration of the column, respectively, $\ddot{u}_p$ and $\ddot{z}_p$ are the lateral and vertical accelerations of centre of mass of the column, and J_p is the moment of inertia of the column.

The kinematic restoring force for the column i is given by the relationship (7):

$$F_{b2}^{i} = \frac{G_i \cdot u_b}{2p_1} \tag{7}$$

where G_i represents the weight of the structure above the PRB system corresponding to the column i.

The restoring force of a column is given by a tangential function of the base displacement (Fig. 5). On account of the nonlinearity in stiffness represented by this function, the response has an inherent stabilising effect. The constitutive law of the elastomeric material is a highly non-linear one. The stiffness of a pendular unit, corresponding to the elastic range (0 to d in Fig. 4) results from the energetical equilibrium under a unit lateral base displacement. The strain energy of a damping unit may be written (8):

$$W_i = \int_V \frac{E_0 \cdot \varepsilon^2}{2} dV \tag{8}$$

in which $\varepsilon = \varepsilon_z \cos\varphi$, $\varepsilon_z = \frac{\varepsilon_0 \cdot z}{h_0}$ and $\varepsilon_0 = \frac{d_0}{l_0}$, where $\varepsilon, \varepsilon_z$ and ε_0 are the strains at the co-ordinate (z and ϕ), z and h_0, respectively, E_0 is the Young's modulus in the elastic region and d_0 the deformation at the co-ordinate h_0. The expression of the strain energy becomes (9):

$$W_i = \frac{2E_0 \cdot \Delta l_0^2 \cdot r_1}{l_0^2 \cdot h_0^2} \int_0^{h_0} \int_0^{l_0} \int_0^{\frac{\pi}{2}} z^2 \cos^2 \varphi \left(\frac{1-c_1}{h_0} z + c_1 \right) \cdot dx \cdot dy \cdot dz \tag{9}$$

in which $c_1 = r_0 / r_1$.

The external work is given by:

$$W_e = \frac{F_{b3} \cdot \Delta}{2} \tag{10}$$

The force caused by the rubber gasket is then given by the following relationships, for the linear response (11) and for the nonlinear response (12):

$$F_{b3l}^{i} = K_0 \cdot d \tag{11}$$

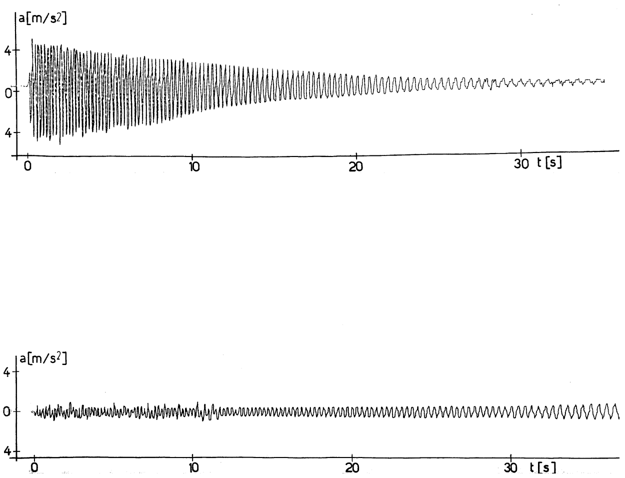
$$F_{b3n}^{i} = \frac{2K_0 d}{\pi} \tan \frac{\pi \cdot d}{2d_c} \tag{12}$$

where:

$$K_0 = \frac{E_0 \cdot d_0^2 \cdot h_0 \cdot r_1 \pi}{6l_0} (3 + c_1) \tag{13}$$

EXPERIMENTAL RESULTS

The experimental research has been carried out on a full scale model. It consists of two rigid reinforced concrete plates of a triangular shape. Each platform has three bearings for the columns. In the clearances between the pendulum and bearings, a rubber gasket was introduced. It was vulcanised in a special matrix. At the ends of the pendulum two steel plates spherically shaped were mounted. The parameters of the system are the radius of the steel spherical callotes (17.5, 21 and 28 cm.) and the dimensions of the rubber gaskets (5, 10 and 15 cm. at the base, named type A, B and C, respectively). A detailed description of the experimental model, the instrumental network and the obtained results has been made in several previous papers (Olariu 1994, 1996). Testing was developed in the following sequence: static loading tests, free vibration tests and forced vibration tests.



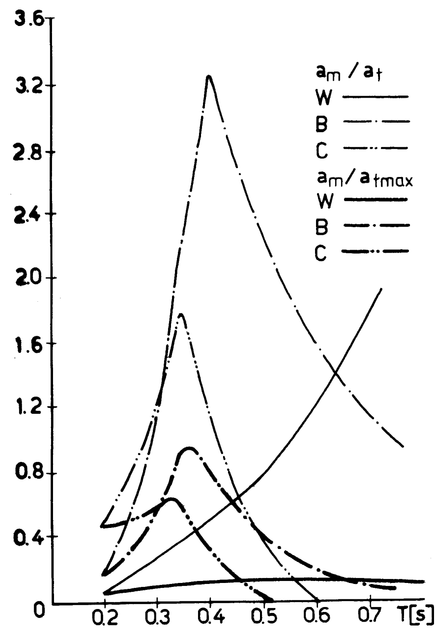


Fig. 6. Time history for the shaking table and for the model. Fig. 7. The spectral ratio a_m / a and $a_m / a_{t\,\max}$

The comprehensive study of all available data of our experimental and theoretical results leads to the following general conclusions:

- the PRB system combines the advantages of kinematic system with those of the LRB ones;

- the experimental and parametric test results demonstrated substantial reductions of the structural response acceleration in comparison of a non-isolated model (Fig. 6);

- the PRB system grants a uniform behaviour for an earthquake acting in any direction;

- the period of vibration is almost independent of the supported mass;

- permanent displacements were found to be very small and not cumulative in successive earthquakes;

- the PRB system grants a constant performance, without decay for a large number of cycles.

EFFECTIVENESS

Figure 7 shows the variation of the ratio a_m / a_t and $a_m / a_{t\max}$ versus the natural period of vibration. As we can see, the ratio between the response acceleration of the model a_m and the maximum acceleration of the shaking table $a_{t\max}$ is lower than 1 in all frequency ranges for all the models. A maximum and constant reduction in accelerations (85-90%) is obtained for the model without rubber (W). The maximum acceleration and ratio are obtained in the case of the sample B, having lo = 10 cm., the peak acceleration being developed. The minimum relative displacements and ratio was identified for the sample W (without rubber) in all the frequency ranges. The maximum displacement is obtained for the sample B.

In evaluating the effectiveness of the passive response-control structures, advantages and disadvantages should be revealed. Some of the advantages are: reduction in the cross-sectional area of the structural elements, in safety conditions, due to the remarkable reduction of the peak acceleration and of the maximum seismic shearing forces, safety of structures under emergency conditions, preventing damages and sliding or rolling of furniture or machines, limiting lateral forces in the retrofitted buildings so as not to overload the existing foundation. As disadvantages we mention the following: uncertainties in the design of passive response-control structures as variability of wind and earthquake loads and variability of structural properties, the choice of the fitted isolation system, the problem of the overturning moment for certain isolation systems, lack of adequate knowledge of response-control systems amongst clients, architects and others. Since the acceleration ratio is very small especially for the system without rubber, the ground motion will not be transmitted into the isolated structure. This is the real effectiveness of a seismic isolation system which does not absorb energy, but deflects it through its properties.

CONCLUSIONS

Passive control includes two families of protective systems: base isolation systems and energy dissipating systems. Base isolation is the only engineering solution that mitigates both interstory drift and high floor accelerations. The method is especially suitable for seismic protection of historical buildings, part of the cultural heritage of a country. The comprehensive study of all available data of our experimental results shows the effectiveness of the PRB system. The PRB system combines the advantages of kinematic system with those of the LRB ones. The experimental study results demonstrated substantial reductions of the structural response acceleration in comparison with a non-isolated model. The system grants a uniform behaviour for an earthquake acting in any direction and the period of vibration is almost independent of the supported mass. Permanent displacements were found to be very small and not cumulative in successive earthquakes. The tests indicates that the long-period motions increase the structural accelerations and the relative displacements between the two plates. The displacements can be effectively reduced by increasing the isolator damping.

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