Seismic Isolation: Earthquake Protection of Buildings

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Abstract— Seismic protection of buildings has a remarkably long history. The latest reveals a great diversity of methods, devices and daring concepts. The paper deals with the protection of buildings by passive control using seismic isolation. The seismic isolation concentrates the effects of ground shaking in specially designed devices implemented in the structure. The principle of the method, its effects and features are briefly presented. The devices used are introduced, providing a glimpse to their past, present state and development. In the study are also given examples of past and present applications, new research and accomplishments around the world. The goal herein is to show the current state and directions of the seismic isolation technology.

Index Terms— **passive, control, past, improvement, isolator, response.**

I. INTRODUCTION

In earthquake resistance design of structures, two general concepts have been used. The first is to increase the capacity of the structures to resist the earthquake load effects (mostly horizontal forces) or to increase the dynamic stiffness such as the seismic energy dissipation ability by adding damping systems (both devices and/or structural fuses). The second concept includes seismic isolation systems to reduce the input load effects on structures. Obviously, both concepts can be integrated to achieve an optimal design of earthquake resilient structures. This chapter is focused on the principles of seismic isolation.

Earthquakes are a natural consequence of the incessant evolution of our planet. Civil engineering is continuously improving ways to cope with this inherent phenomenon. Over the last decades, various methods emerged on the background of technological development. One method is to control the structural performance during earthquakes.

The seismic response control is governed by the energy balance equation [1-3]:

$$E = E_k + E_s + E_h + E_v \qquad (1)$$

where E is the energy induced by the seismic shaking, Ek is the kinetic energy, E_s is the elastic strain energy, Eh is the hysteretic damping energy, E_v is the viscous damping energy. The seismic isolation system (SIS) is used in order to decrease the earthquake energy (E) acting on the structure.

Seismic isolation is a passive structural control system because its operation does not depend on external energy sources. It relies only on the properties of its constituent materials (elasticity, yielding, friction coefficient, shear modulus, etc.). It may become also a part of semi-active or active systems, which needs an external power supply in order to function properly.

The goal herein is to present the current state and future directions of the seismic isolation technology.

II. EFFECTS OF SEISMIC ISOLATION

The concept of base isolation is quite simple. The system decouples the building or structure from the horizontal components of the ground motion by interposing structural elements with low horizontal stiffness between the structure and the foundation. This gives the structure a fundamental frequency that is much lower than both its fixed-base frequency and the predominant frequencies of the ground motion [4]. This shift of natural period causes a drop in spectral acceleration for the typical earthquake shaking - fig. 1 a). This improvement is accomplished at the expense of increasing lateral displacement - fig. 1 b). The damping by energy dissipation influences the displacement and the acceleration response as it is shown in the schemes 1 a), and 1 b). The local soil conditions have a great impact on the reliability of the base isolation. In stiff soil conditions a significant reduction in spectral acceleration is attained while in soft soil the adverse occurs - fig. 1 c) [1,2].

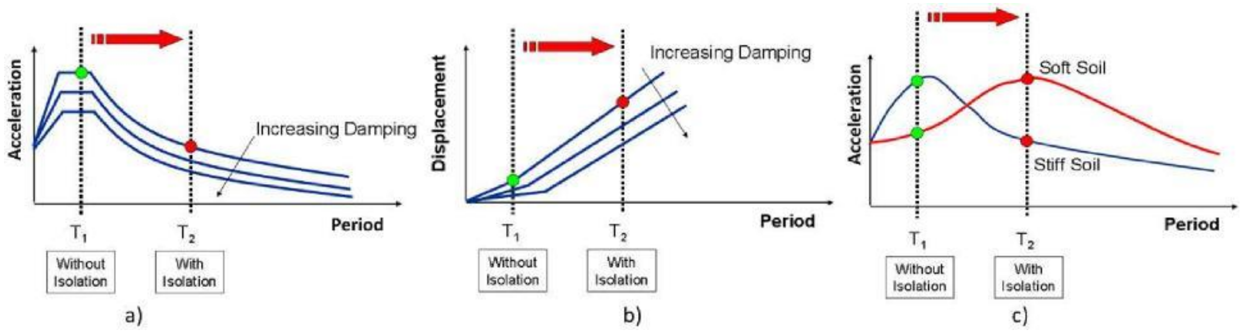


Fig. 1 – Effects of base isolation: a) on spectral acceleration, b) on lateral displacement, c) for different soil conditions

III. FEATURES OF SEISMIC ISOLATION

Seismic isolation is used for both new projects and retrofit existing buildings. During retrofitting the building's functionality is not disturbed.

The resultant forces on structural and non-structural elements of the building are significantly reduced. This fact provides great freedom in architectural and structural design. Contents-related damage is minimized due to reduced acceleration response [5].

Attention shall be given concerning the following issues: ensure a gap around the building to allow displacement, proper detailing for the utility connections to avoid displacement related damage, avoid torsion amplifications caused by mass eccentricities in the superstructure. Design must consider a certain resistance to small earthquakes and wind action.

IV. DEVICES USED FOR SEISMIC ISOLATION

The most popular types are elastomeric based bearings and sliding bearings. A new approach is being developed in the form of three-dimensional protection systems.

A. Elastomeric Bearings

It consists of steel and rubber, it made of sandwiches of soft rubber sheets and hard steel plates as shown in the Photograph. It works as a bearing to sustain the weight of the building and is able to move the building laterally. Soft rubber reduces the building vibration to slow shaking, and hard steel plate contributes to sustain the weight of building.

Based on their main properties and compounds there are two sorts of elastomeric bearings: Natural and Synthetic Rubber Bearings (NRB) and Lead Rubber Bearings (LRB).

a) Natural and Synthetic Rubber Bearings (NRB)

As it can be seen in the Fig. 2 a), NRB are made of alternating elastomeric layers and steel shims vulcanized or glued together. The elastomeric layers provide lateral flexibility and elastic restoring force. The steel plates reinforce the bearing by providing vertical load capacity and preventing lateral bulge. A rubber cover protects the ensemble. Mounting plates connect the device to the structure above and below. Depending on the elastomeric compounds used, NRB are available as either low damping or high damping. The low damping bearings are used in conjunction with supplementary damping devices. The high damping ones are able to provide sufficient inherent damping and eliminate the need of other tools.

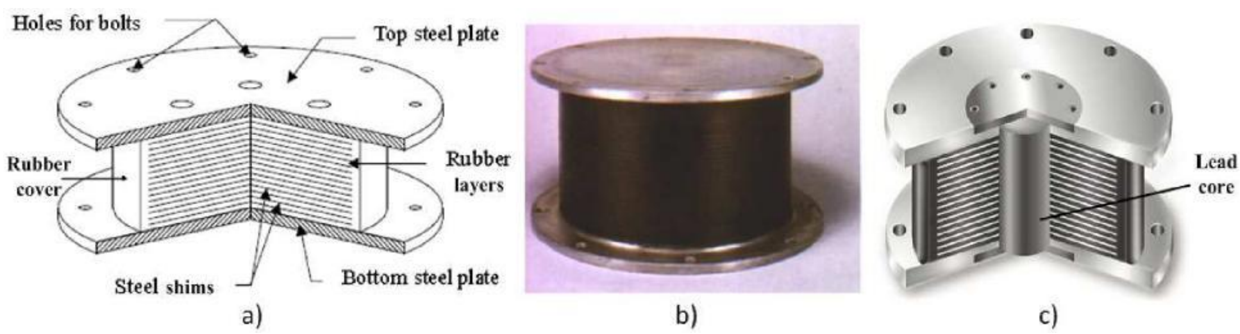


Fig. 2 – Elastomeric bearings: a) Natural Rubber Bearing (NRB), b) elastomeric bearing device, c) Lead Rubber Bearing (LRB)

Studies are being performed to obtain improved and cheaper devices. An example is the Hollow Rubber Bearing (HRB). Due to its geometry the stiffness is reduced and thus is prone to large displacements - Fig. 3 a) [6]. A cheap solution for non-engineering structures in developing countries may be the Scrap Tire Pads (STP), studied in Japan - Fig. 3 b), c) [7].

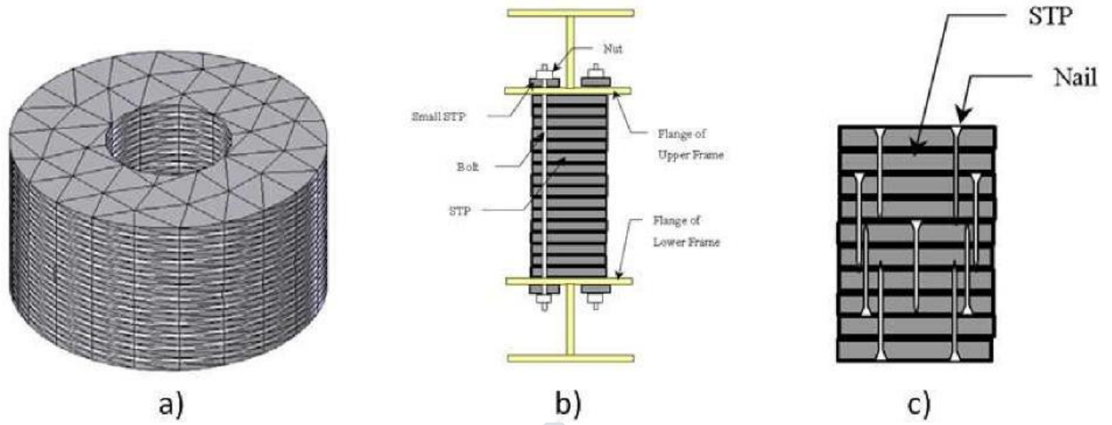


Fig. 3 – Recently studied devices: a) meshed finite element model of a HRB, b) bolted STP, c) nailed STP

b) Lead Rubber Bearings (LRB)

They are similar to the NRB, but contain a lead core - Fig. 2 c). The steel shims confine the lead plug and force it to deform in shear. Along with this deformation, dissipation of energy takes place.

B. Sliding Bearings

These types of bearing achieve the isolation at the contact surface between its uncoupled components that move relatively one to each other. They rely on friction to dissipate energy.

First use of sliding bearings dates back to antique Persia (today Iran). There are evidences of pouring sand between the ground and the bearing walls of some historical structures in Iran. This would create a sliding mechanism for the structure during earthquakes [8]. The foremost modern base isolation system patented was a sliding one. It was proposed by the English medical doctor J. A. Calantarients in 1909 [4]. He suggested the separation of structure from ground through a layer of fine sand, mica or talc, thus allowing the structure to slide when subjected to seismic movement.

Current devices are mainly based on friction between stainless steel and Teflon. Depending on their sliding surface geometry, two kinds of sliding bearings are distinguished: Flat Slider Bearings and Curved Slider Bearings (referred to as FPS – Friction Pendulum System).

i. Flat Slider Bearings

Sliding takes place along a horizontal plane. They don't have a restoring reserve and are used in parallel with other devices, usually elastomeric bearings. In Fig. 4 a), a section through a pot bearing is presented. The pot includes a slice of elastomeric material that permits rotations [5].

Another similar sliding bearing is the rail roller bearing. The sliding occurs on two orthogonal rails in horizontal direction - Fig. 4 b) [9].

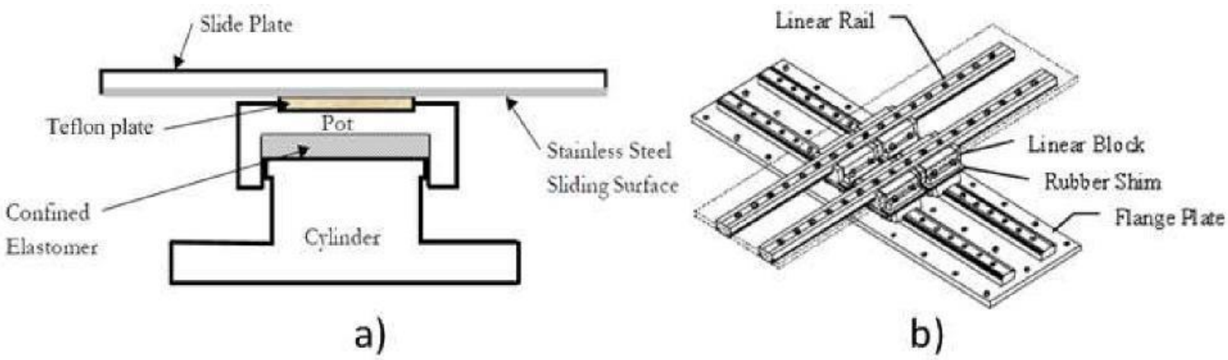


Fig. 4 – Horizontal sliding bearings: a) pot bearing, b) rail roller bearing

In Fig. 5 it is presented the layout of base isolation using rail roller bearings implemented by the Japanese company THK. The rail sliding device has a very low friction force and it is accompanied by laminated rubber isolators, for restoring and viscous damping devices. Due to its tensile strength, it can be used to isolate high-rise buildings [10].

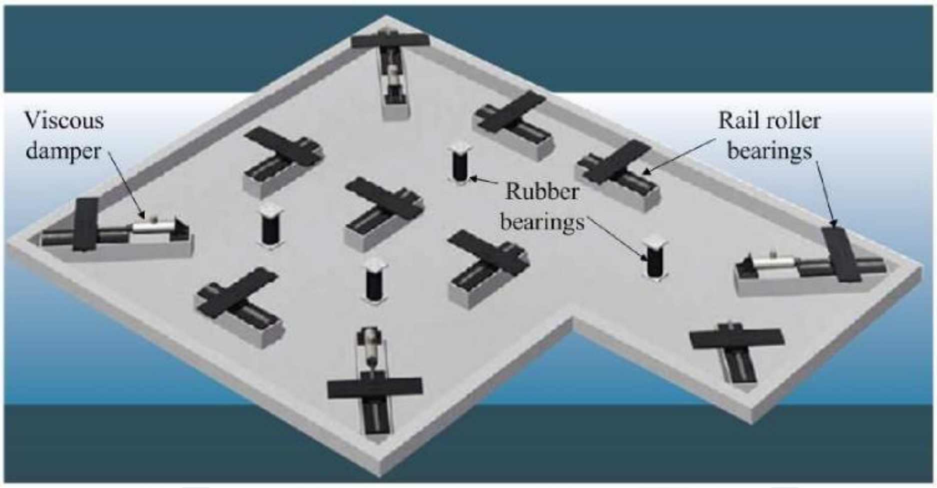


Fig. 5 – THK base isolation system

New materials are being tested nowadays to obtain cheaper devices intended for non-engineering use in developing countries. Satisfactory results were obtained for wood-stone and granite-marble contact surfaces [7, 11].

ii. Curved Slider Bearings

The Friction Pendulum System (FPS) is a patented device with spherical sliding surface which has been extensively used. The friction coefficient provides resistance to service loads. Once the friction coefficient is overcome the articulated slider moves on the concave surface. The lateral travel is accompanied with a vertical movement of the mass that provides a restoring force. A scheme of a FPS with its main components is shown in Fig. 6.

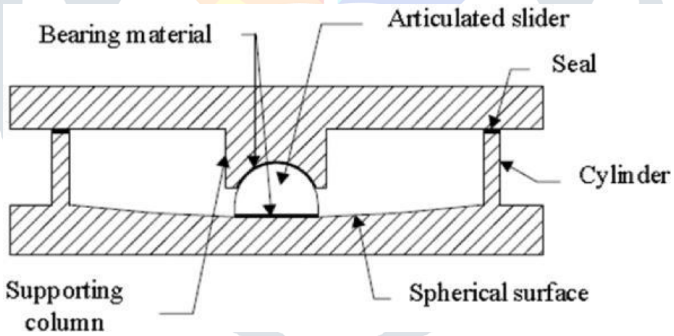
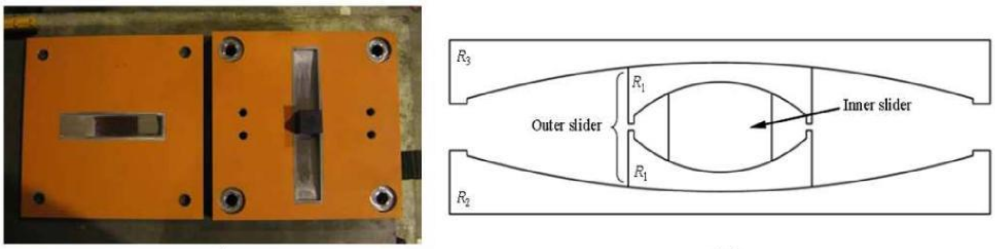


Fig. 6 – Scheme of the Friction Pendulum System (FPS)

New improved devices are being studied. The Trench and Trajectory Friction Pendulum System (TFPS) have different properties on the two orthogonal directions - Fig. 7 a) [12]. It is recommended for buildings possessing very different natural frequencies in two directions. The Triple Pendulum (TP) bearing is a multi-stage bearing that progressively exhibits different hysteretic properties at different stages of displacement response. It incorporates four concave surfaces and three independent pendulum mechanisms - Fig. 7 b). The stiffness and damping of the three mechanisms is selected based on multiple levels of seismic demand [13].



a) b)

Fig. 7 – Optimized Friction Pendulum Systems: a) Trench and Trajectory Friction Pendulum System (TFPS), b) Triple Pendulum (TP) bearing

C. Three Dimensional Isolation Systems

This kind of isolators is still in the testing stage and until now good results were obtained. They provide not only horizontal but also vertical isolation and control against rocking motion. This system is reliable for very sensitive structures like nuclear power plants, hospitals, museums etc. Herein is presented the solution developed by Kozo Keikaku Engineering Inc., Japan - Fig. 8. It is designed for a three story residential building - Fig. 8 a). The system components for the horizontal direction are high damping laminated rubber bearings and oil dampers. For the vertical direction there are air springs, sliders and oil dampers with rocking suppression - Fig. 8 b). It is a passive structural control system [14].

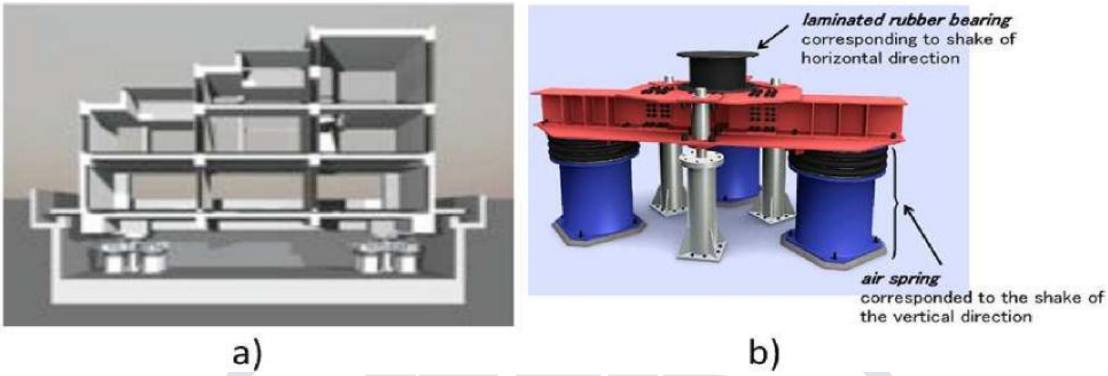


Fig. 8 – KKE Three Dimensional Seismic Isolation System: a) structure elevation, b) main components

V. REGULAR AND INNOVATIVE ARRANGEMENTS OF ISOLATORS

The most common configuration is to install a diaphragm immediately above the isolators. This permits earthquake loads to be distributed to the isolators according to their stiffness. For a building without a basement the isolators are mounted on foundation pads and the structure constructed above them as shown in Fig. 9 a). If the building has a basement, then the options are to install the isolators at top, bottom or mid-height of the basements columns and walls as shown in Fig. 9 b) [5].

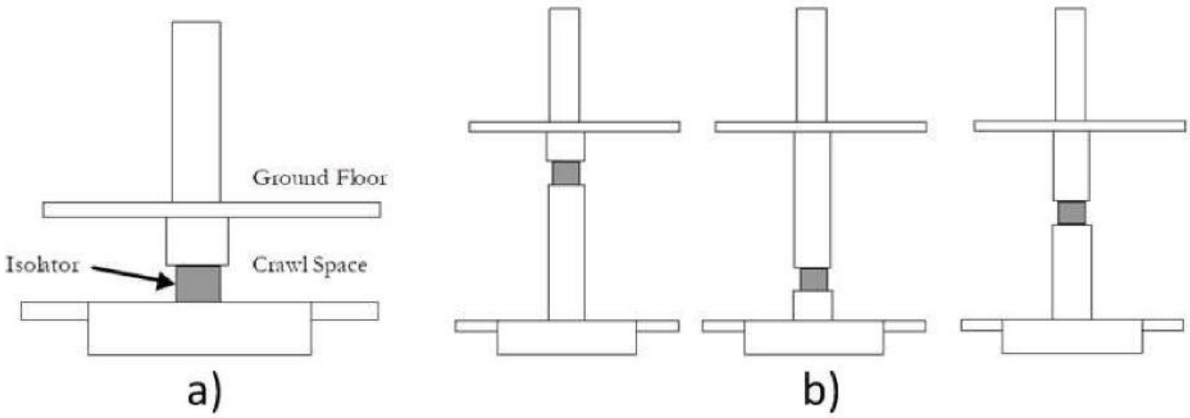
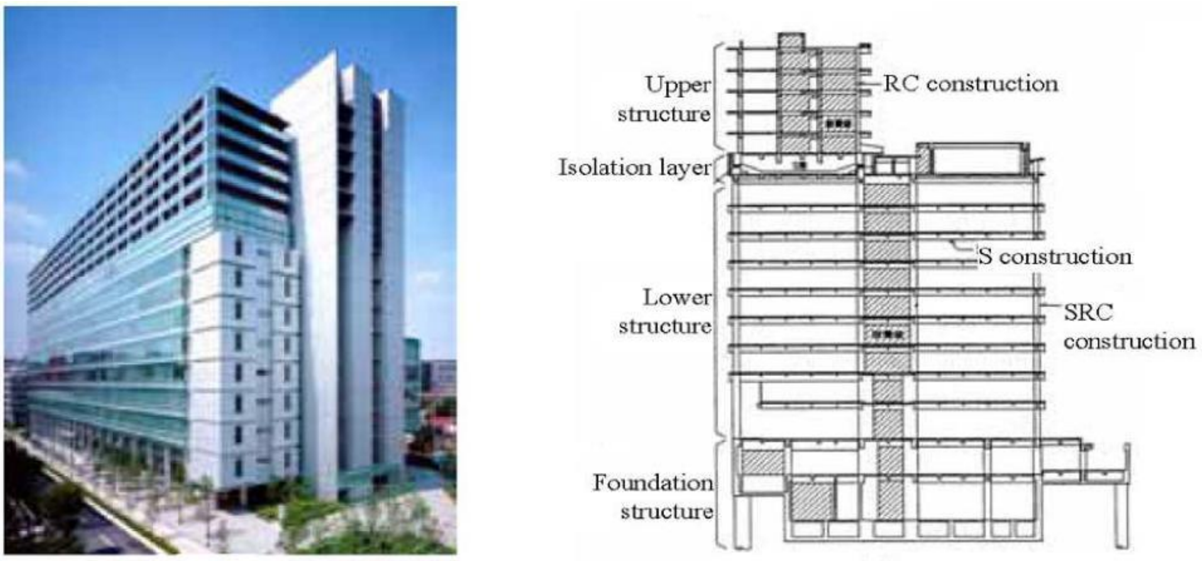


Fig. 9 – Common location of the isolators: a) for structures without basement, b) for structures with basement

By choosing other locations for the isolators inside the structure, a new dynamic response is achieved. This method is seldom used and still in research phase. Two of these methods that have been tested and successfully applied are: the middle-story isolated structural system and the self mass damper control system.

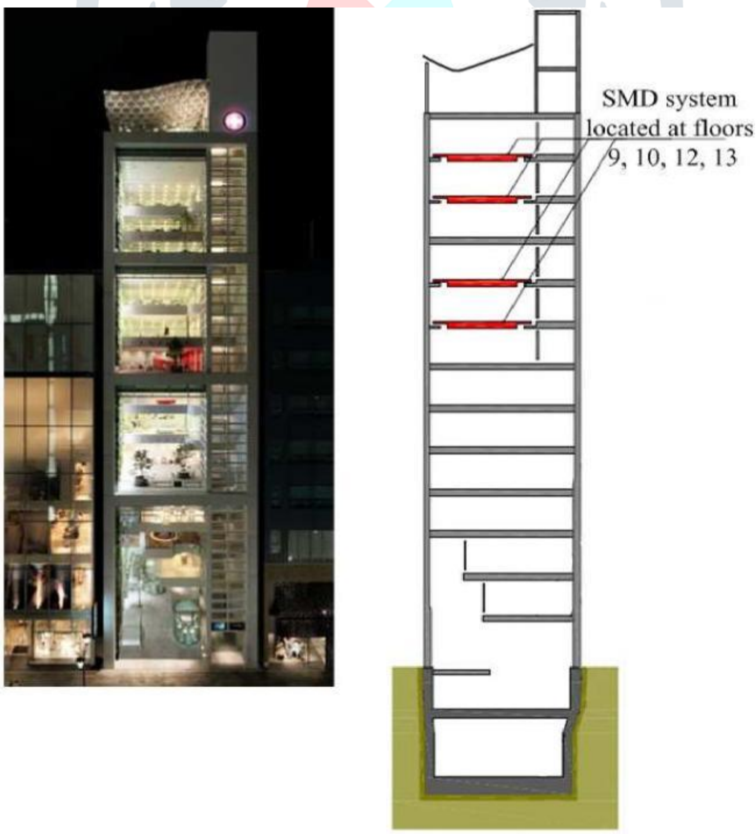
Middle-story isolated control system: the building is divided into two parts by interposing an isolation layer at a certain story, above the first floor. The upper structure behaves like a base isolated structure. It also induces a mass damper effect to the lower structure, thus achieving an improved dynamic response. A great freedom in architectural and structural planning is possible by using this method. An example is "Iidabashi First Building, First Hills Iidabashi" building from Japan. The lower section of this construction is a steel structure for offices and the upper section is a reinforced concrete structure for residential use - Fig. 10. Natural rubber laminated isolators and lead dampers are used [15,16].

Self-mass damper control system (SMD): this system is in use at "Nicolas G. Hayek Center" in Japan. It emerged from the need of the high seismic resistance design to meet the daring architectural requirements. The mass damping solution is used, but without additional mass. The existing floor plates are used as mass dampers to absorb the seismic energy. Certain floors are disconnected from the structure through a combination of slider and high damping rubber bearings - Fig. 11 [17].



a) b)

Fig. 10 - "Iidabashi First Building, First Hills Iidabashi", Japan; middle story isolated system : external view, b) structure elevation



a) b)

Fig. 11 - "Nicolas G. Hayek Center", Japan; self mass damper system: a) external view, b) structure elevation

VI. CONCLUSIONS

When its application is consistent with the structural configuration of a historic building, the base isolation is a very effective way to protect cultural heritage. The possibility of reducing and even avoiding strengthening works of the structures above the isolation interface is the most attractive performance from the point of view of the philological criterion that rules the rehabilitation work. Seismic protection of buildings by seismic isolation is continuously improving since its early stages. New materials and shapes are contributing to the development of recent high performance devices. Architectural innovations are encouraged by the enhanced structural response achieved through seismic isolation. Developing countries may also benefit from this technology especially in the case of non-engineering structures.

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