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SEISMIC ISOLATION STRATEGIES FOR MAJOR BUILDINGS

Charles CYNOBER[1], Mauro SARTORI[2], Burak TÜRKDÖNMEZ[3], François TRONEL[4]

ABSTRACT

Based on old construction codes, buildings have been designed to not collapse on their occupants. With the recent codes, base isolation has been introduced to improve the seismic protection of the building itself and of the non-structural components and the equipment.
Freyssinet has developed a complete competency on base isolation that includes the building isolation system design, the devices design, production and tests and their installation. The isolation strategy depends mainly on the seismic zone, the acceleration and displacement specifications and the available space for installing the devices. The Marmara hospital, which is one of the main hospital of the Istanbul area, Turkey, has been retrofitted with Lead Rubber Bearings (LRB) and sliding bearings. The Bucharest City Hall, a historical building and a crisis management centre in Romania, has been retrofitted with High Damping Rubber Bearings (HDRB) associated with Fluid Dampers (FD). The Taipei Museum of Art, Taiwan, has been isolated with Pendulum Systems (PS).
Another main advantage of base isolation is a potential cost reduction of projects. It leads to such a base shear reduction on the superstructure and such a force reduction on the substructure that a significant amount of concrete and rebar can be saved. This saving generally covers the additional cost of seismic devices that is typically about 2-3 % of the building's total cost.

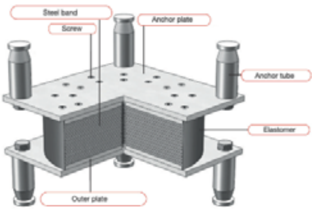
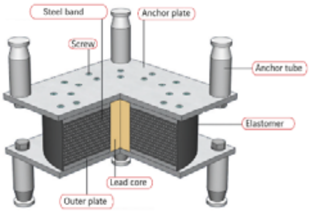
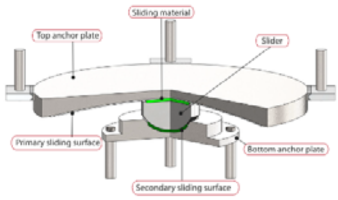
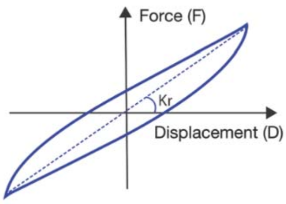
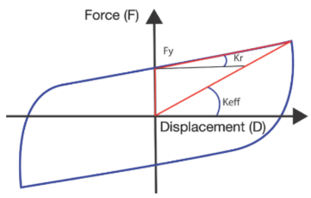
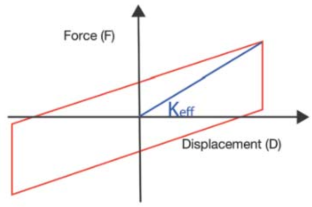
Keywords: Base isolation; hospital; museum; historical building

1. INTRODUCTION

In areas subjected to large earthquakes, the seismic protection of major buildings is a priority for the society. Operational administrative centres, fire stations and hospitals are required for the crisis management. Other buildings such as schools and main museums represent as well a huge social value. Based on old construction codes, these buildings have been designed to not collapse on their occupants. With the recent codes, base isolation has been introduced to improve the seismic protection. First, an isolated building will remain elastic for the design earthquake. Moreover, the base isolation also protects the non-structural components and the equipment such as control rooms, scanners and pieces of art.
There are different technologies of isolators, detailed by the Table 1.
These three isolators provide distinct working points to the isolated structure as shown by Figure 1. HDRB have moderate damping, from 10 to 16 %. LRB have a high damping, up to 35 %. PS have moderate-high damping and are used for larger periods than rubber bearing isolators. These three kinds of dampers can be associated with FD in order to increase the total system's damping.

[1]Seismic engineer, Freyssinet, Rueil Malmaison, France, charles.cynober@freyssinet.com
[2]Technical director, FPC Italia, Milano, Italia, mauro.sartori@freyssinet.com
[3]Project director, Freysaş, Istanbul, Turkey, burak.turkdonmez@freysas.com.tr
[4]General manager, Freyrom, Bucharest, Romania, francois.tronel@freyssinet.com

Table 1: Properties of the different technologies of isolators

Device name	Isosism® HDRB	Isosism® LRB	Isosism® PS
Meaning	High Damping Rubber Bearing	Lead Rubber Bearing	Pendulum System
Device scheme			
Behavior law			
Spring function	Rubber properties	Rubber properties	Pendulum’s radius
Damping	Rubber properties	Lead ductility	Friction between primary sliding surface and sliding material

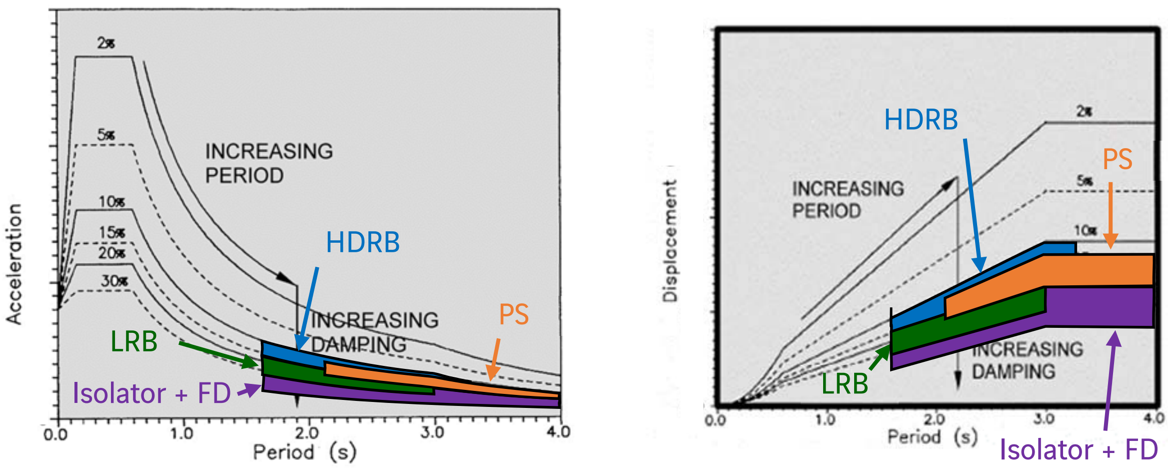


Figure 1: Working points of the different technologies of isolators

A superstructure is efficiently isolated when there is a sufficient gap between the frequencies of its own vibration modes and the one of the isolation system. As a result, stiff superstructures are generally isolated with rubber bearings, while flexible superstructures are typically isolated with pendulum systems. This is illustrated in the next three chapters with applications to three major buildings.

2. ISOLATION OF THE MARMARA HOSPITAL WITH LRB AND SLIDERS

The Başibüyük Marmara University Hospital is located in Maltepe district, in the Başibüyük quarter, in the Asiatic side of the town, on the Coast of Marmara Sea. The hospital is located in first category zone, according to Turkish code, with 0.4g of peak ground acceleration.
The layout of the building with a total area of about 112000 m² and a capacity of about 750 beds is shown in the Figure 2. The structure is made of 16 blocks that have from 4 to 12 floors, separated by

expansion joints. The foundation level is not constant and shared among three different levels: -14.5 m, -8.96 m and ±0.00 m.

Figure 2: Layout of the Marmara hospital

The building never started his duty, despite its construction started in 1991. After the introduction of the seismic standard in 1998, the structure has been retrofitted in 2002 through the introduction of concrete shear walls and column jacketing.
Nevertheless, after the incoming of the current seismic standard in 2007, the retrofitting recently performed did not satisfy the request of the new standard. Only the car park, after the seismic evaluation, was considered adequate for the both levels of safety and did not require any further operation of retrofit. On the other hand, all the rest of the structure needed proper operation of adaptation to the standard.
The current seismic code foresees that on existing buildings a performance-based evaluation on all the structural elements is performed on two different levels of safety. The first level, called Life Safety (LS) considers the application of a response spectrum obtained by an earthquake with 2% of probability of exceedance in 50 years (2475 years return period). The second level called Immediate Occupancy (IO) considers the application of a response spectrum with 10% of probability of exceedance in 50 years (475 years return period).
The project's specification includes three constraints:

- For the IO event, base shear forces limited to 10 % of the total weight.
- For the LS event, Base shear forces limited to 15 % of the total weight.
- For the LS event, displacement limited to 500 mm.

The optimal solution that was able to satisfy these requirements, granting at the same time a satisfactory a good architectonical equilibrium, was the base isolation of the whole structure linking all the 16 blocks in one rigid element. At a preliminary design stage, a single degree of freedom (SDOF) model has been used to define the working point.

Table 2: Main parameters of the Single Degree Of Freedom System

Number of Isolators	V_{seism} (G+0.3Q) (MN)	d_{max} (mm)	K_{eff} (kN/mm)	Energy dissipated per cycle EDC (kNm)	Equivalent viscous damping ξ
687	1360	±380	521	140926	30%

The stiffness and damping indicated in Figure 3 represent the whole isolation system. On the basis of the characteristics indicated in Table 2 the maximum displacement generated by the response spectrum with return period of 2475 years was of 380 mm.

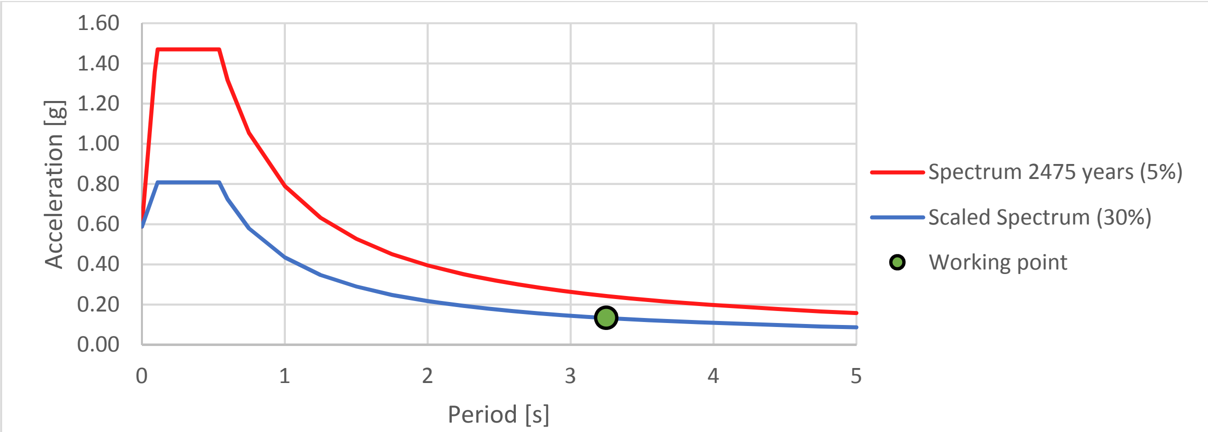


Figure 3: Seismic response of the Single Degree of Freedom (2475 y. return period)

The solution found to provide this working point was the association of LRB, which provide the required damping, and sliding bearings, which carry out the vertical load without adding horizontal stiffness to the system.
These devices had to be introduced in an existing structure. This implies to cut all the columns, which was one of the challenges of this project. Up to five non-adjacent columns were cut at a time. A nonlinear time history analysis has been performed and two targets where achieved:

- Validating the characteristics defined during the preliminary study.
- Validating the building's stability during cutting operation.

Initial type tests (ITT) of the LRB devices have been performed at the laboratory of Eucentre (European centre for training and research in earthquake engineering) in Pavia, Italy while the Factory Production Control (FPC) tests were performed at Isolab, which is the laboratory of Freyssinet for dynamic tests, at Montebello della Battaglia (PV), Italy. Sliders have been tested at Isolab.

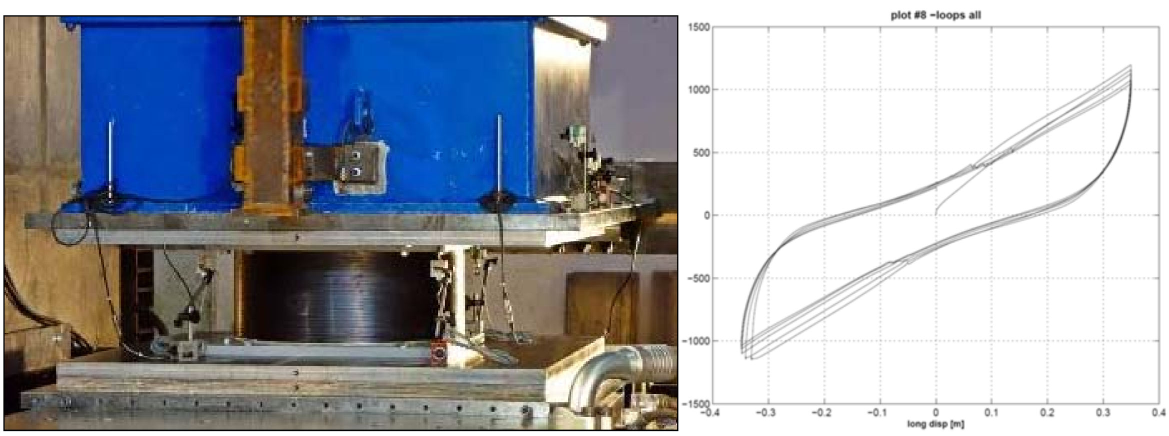


Figure 4: Test on LRB at Eucentre

Due to different levels of foundation over this element and in order to let the building free to move over the ground level, the primary isolation level has been located on the second level. For the elevators and staircases, which remain fixed to the isolated superstructure, a secondary isolation level has been located at the basement.

3. ISOLATION OF THE BUCHAREST CITY HALL WITH HDRB COMBINED WITH FD

The Bucharest City Hall is a 6-floor building (basement, ground floor, R+4) having a plan area of 3800 m². It was built between 1906 and 1911, with 5 floors. A floor was added in 1948 and the meeting hall on the first floor was remodelled in 1968.

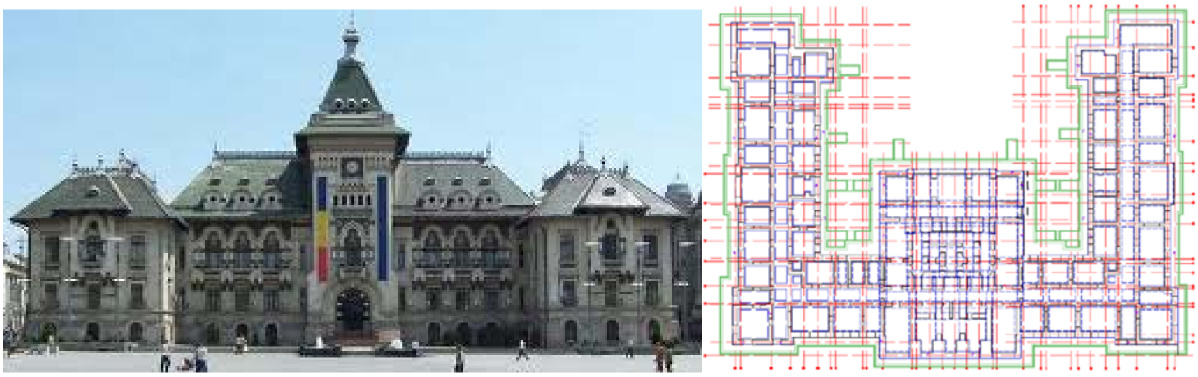


Figure 5: Front view of the Bucharest City Hall (left) and layout of the ground floor (right)

Its plan view presents an “E” shape with a central part and two aisles. The structure is made of masonry walls having a thickness from 0.40 to 1.10 m and reinforced concrete slabs.
It was exposed to four earthquakes having a magnitude of 6.7 to 7.4 between 1940 and 1990. It has been deemed to be unsafe and highly susceptible to collapse during future severe earthquakes.
A classical reinforcing solution was proposed in 1998, including:

- Additional shear walls lining the existing ones.
- Vertical cuts to split the building in three sections, and joints of 10-15 cm.
- Reinforcement of the foundations with injection of water and sodium-silicon-dioxide based cement up to 2.5 m depth and addition of a concrete basement slab of 40 cm thickness.

This invasive solution was not implemented. A seismic base isolation system has been designed, instead, by A Iordachescu, from University of Architecture and Urban Planning, and E. Iordachescu, from S.C. PROESCOM SRL. Considering an isolation period of 3.3 s, this solution meets the requirements of the existing codes and was estimated to produce a saving of 5 % over the moment-resisting frame option.

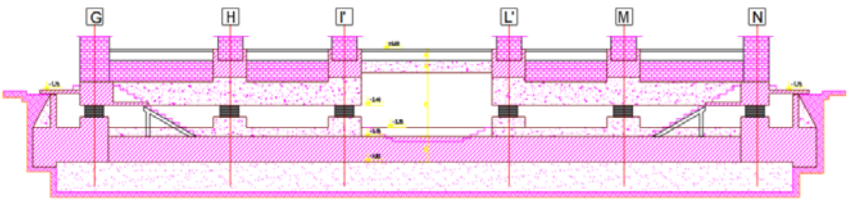


Figure 6: Typical layout of the isolation level

Freyssinet was awarded for the supply and installation of seismic devices, including the cutting of brick walls, creation of support frames below and above the isolation level, opening a trench around the building, installation of perimeter joints, loading of the isolators and load transfer using flat jacks.

Figure 7: HDRB before grouting the lower frame (left) and during the load transfer (right)

The long predominant periods of the recorded earthquakes and undesirable side effects due to the soft soil conditions lead to an isolation system that shows a large displacement capacity and a high damping. This was obtained with High Damping Rubber Bearing associated with Fluid Dampers.
The seismic devices consist in 262 rubber isolators Ø 1000 mm and Ø 1050 mm and 36 viscous dampers of 1750 kN. The design movement of all the devices is equal to ±700 mm, with a seismic velocity of 1.5 m/s. The devices have been designed and tested according to the European Standard EN15129, before being installed. Both the rubber isolators and the viscous dampers have been successfully tested at the maximum design velocity at the University of California Laboratory located in San Diego (USA).

Figure 8: Tests on FD (left) and HDRB (right) at San Diego

4. ISOLATION OF THE SOUTHERN BRANCH OF NATIONAL PALACE MUSEUM, TAIWAN, WITH PENDULUM SYSTEMS

The museum is located at Taibao City in the Chiayi County, Taiwan and the story of the construction begins at the end of 2004 with the approval by the government of the project created by the Taiwan-based firm Artech Inc.

The Southern Branch Museum, originally scheduled for completion in 2008, was later postponed as a result of contractual disputes as well as the Typhoon Morakot, which created a flooding that measured 10.3 meters tall in the foundation. In October 2010, a project revision plan was completed and the building of the Southern Branch Museum was reinitiated to come up to the end of construction by the end of 2015.

The project cost was of USD 268 million spread over 70 hectares (700,000 square meters). The building is both earthquake resistant and flood resistant, thanks to measures taken by the designers to ensure isolation from ground level to protect the building from seismic shocks and also to have flood and drought-resistant capabilities, making it a gold-level "smart" building as per the EEWH green building certification system in Taiwan.
Taiwan is situated in a seismically active zone, on the Pacific Ring of Fire, and at the western edge of the Philippine Sea Plate. Geologists have identified 42 active faults on the island, which caused between 1901 and the year 2000 91 major earthquakes, 48 of them resulting in loss of life. Seismic protection of strategic buildings is hence of primary importance. Museums are of course among them, for the inestimable treasures they contain.
The very high seismic demand moved the designer to adopt a seismic isolation system. The sliding pendulum technology appeared to be the most adapted. The structure is indeed characterized by a strong irregularity in plan. The columns layout has a waved shape as shown in the Figure 7. Pendulum systems have a stiffness that is proportional to the weight of the structure, which leads to always keep the centers of mass and stiffness at the same point. There is no eccentricity even though the load distribution shows a very irregular layout. The superstructure is not susceptible to rotate around a vertical axis.

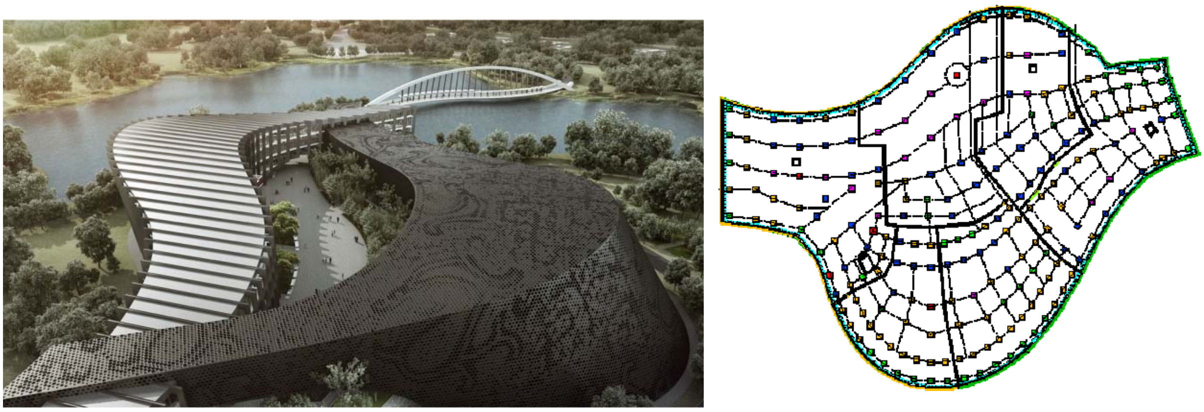


Figure 7: Aerial view of the museum (left) and layout of the columns (right)

In order to not increase too much the shear force on the columns, a 3% dynamic friction coefficient and a radius of 3962 mm have been chosen. Sliding pendulums with vertical load capacity up to 20000 kN and ±500 mm of displacement were designed, produced and tested by Freyssinet according to the designer specifications.

Table 3: Main Figures of the Isolation System

Device	**Quantity**	**Vertical Force [kN]**	**Displacement capacity [mm]**	**Effective Stiffness K_{eff} [kN/mm]**	**Effective Period T_{eff} [sec]**	**Effective Damping ξ_{eff} [%]**
PS 20000/1000	5	20.000	±500	3.98	3.45	16
PS 12500/1000	17	12.500	±500	2.65	3.45	16
PS 10000/1000	60	10.000	±500	2.16	3.45	16
PS 6500/1000	83	6500	±500	1.49	3.45	16
PS 4000/1000	45	4000	±500	0.91	3.45	16

The effective period T_{eff} is calculated as:

$$T_{eff} = 2\pi\sqrt{\frac{V_D}{K_{eff}\, g}} \tag{1}$$

With K_{eff} the effective stiffness of the sliding pendulum for the design displacement:

$$K_{eff} = \frac{V_D}{R} + \mu\frac{V_D}{D_D} \tag{2}$$

In the expressions (1) and (2) V_D is the dead vertical load, D_D is the design displacement and R being the equivalent radius of the device.

All the devices have been tested full scale at Eucentre laboratory in Pavia (Italy) and at University of California – S.Diego (UCSD). In particular tests at velocities typical of the service situation, like the case of wind and braking, and dynamic tests with a different number of fully reversed cycles at different seismic displacement at velocity of 550 mm/s were performed. After being successfully tested, the installation started.

Figure 8: General view of the installed sliding pendulum

5. CONCLUSIONS

Seismic base isolation is a relevant solution to reduce the shear force on buildings during earthquakes. Different technologies have been presented: High Damping Rubber Bearing, Lead Rubber Bearing, Pendulum Systems and Fluid Damper, together with a guide to choose between these solutions.
Three base isolation projects have been described. For the Marmara hospital, LRB have been used to provide 30 % damping. For the Bucharest City Hall, FD have been associated with HDRB to provide more than 30 % damping. For the Southern Branch of the National Palace Museum of Taiwan, PS were implemented to isolate a superstructure presenting a very irregular layout, with a great isolation, close to 3.5 s.
Base isolation is now compulsory for the seismic protection of specific building in some countries such as hospital in Turkey. This is due to their ability to protect not only the superstructure but its content as well. Its implementation also revealed to be more cost effective than a traditional retrofit, by 5 % in the case of the Bucharest City Hall.

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