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USE OF PENDULUM ISOLATORS IN SANTIAGO, CHILE: TWO PRACTIC EXAMPLES

L. Breschi[(1)], J. Bielefeldt[(2)], M.G. Castellano[(3)]

[(1)] *Professor at Pontificia Universidad Católica de Chile, Partner Director at VMB Ingeniería Estructural, lbreschi@vmb.cl*
[(2)] *Partner, VMB Ingeniería Estructural, jbielefeldt@vmb.cl*
[(3)] *Senior Research Engineer in the R&D Department, FIP Industriale, gabriella.castellano@fip-group.it*

Abstract

The use of pendulum isolators in Chile is more recent than that of elastomeric isolators. In the last years, since 2011, two commercial/office buildings have been seismically isolated through pendulum isolators. These two buildings are located in Santiago, thus the seismicity is similar, with PGA of 0.4.

The building Nueva La Dehesa is an office building of more than 25.000 m^2, with some commercial activities in the first two floors. The building has 8 floors and 4 underground floors for parking. The isolators are located just below the ground level, on top of the columns.
The project consists also in an identical building that has no protection system. The idea of this was to see the differences between a protected building and a non-protected one. The results after the last earthquake are clear, the non-protected building suffered several damages on the elevator shaft. The building couldn’t use elevators until a professional fixed them. Needless to say, damage like this can’t happen to buildings like hospitals, airports, and public departments, given the importance they have after seismic events.

The Kennedy building is a commercial building located in one of the most exclusives areas of Santiago. Its protection system worked accordingly after the recent seismic events. This proves again the effectiveness of the technology.

The design has been carried out through nonlinear time history analyses.

The pendulum isolators for the two buildings were fabricated with Ultra-High Molecular Weight Poly-Ethylene (UHMW-PE) as sliding material. Such technology of pendulum isolators, developed in Europe, allows the isolators to sustain a large number of cycles without any damage on the sliding surface. The equivalent radius of curvature of the isolator is 3.1 m for the Kennedy building, and 3.7 m for the Nueva La Dehesa building. The design displacement is ranging from 250 mm to 350 mm.
Type Tests have been carried out in the Seismic Response Modification Device Testing Laboratory of Caltrans at the University of California at San Diego, according to the Chilean Standard.

Keywords: Pendulum Isolator; Ultra-High Molecular Weight Poly-Ethylene (UHMW-PE).

1. Introduction

The movement induced in the Building due to a seismic event can be modified through the presence of seismic isolators. This modification must diminish the solicitations on the Building, but in order for the system to work this way, it depends exclusively on the elements used to produce such isolation.
Present study shows the application of this technology, and its consequent response against seismic events from recent data, but this time through devices known as friction pendulum isolators, which have characteristics that make them a really easy and intuitive application device, and also very trustworthy on its real response.

2. Theoretical Development of Pendulum Isolators

A Pendulum Isolator is a mechanical system that uses the concept of a simple pendulum to achieve a desired response in a vibratory system with the intention to reduce accelerations.
In Fig. 1 you can see a simple pendulum where the famous movement law arises, whose period is independent of the mass. As discussed below, this is very useful at the time of designing an isolation system inspired on this concept.

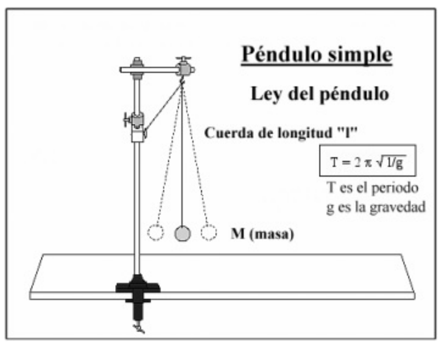

Fig. 1 – Simple Pendulum

One of the main fundamental characteristics of a pendulum is its self-centering capacity, which forces the mass to always go back to its initial rest position.
Considering the above, a structure of a certain mass “m” can be isolated having it supported by isolators with a spherical surface characterized by a certain radius of curvature “R”, and a certain friction coefficient μ. When the friction coefficient is equal to zero, if the radius of curvature is equal to the length of the simple pendulum in Figure 1, the period of the isolated structure is equal to that of the simple pendulum in Figure 1. .
However, some friction is needed to provide some energy dissipation to the isolation system, useful to control the horizontal displacements.

The theoretical foundations are presented below:

Applying the movement equations to the systemof mass “m” isolated with pendulum isolation system with radius R and friction coefficient , we can obtain:

$$m\ddot{x} = -mg\sin\theta - mg\mu\cos\theta \tag{1}$$

Where:

- m = Mass of the system
- x = Displacement
- θ = Angle of the rotation axis from the vertical
- μ = Friction coefficient between slider and spherical surface
- ϑ = Effective Damping

If the angle θ is small, we can have

$$m\ddot{x} = -mg\frac{x}{R} - mg\mu \tag{2}$$

Sorting out we have,

$$\ddot{x} = (\frac{1}{R} + \frac{\mu}{x})x \tag{3}$$

The solution to this homogeneous differential equation is the below:

$$g(\frac{1}{R} + \frac{\mu}{x}) = \omega^2 \tag{4}$$

The frequency of the system would be:

$$\omega_{SIS} = \sqrt{(\frac{g}{l} + \frac{\mu g}{x})} \tag{5}$$

If this frequency is identic to the frequency of the basal movement, it would be possible to obtain a null movement on the mass m. Summarizing the equations that regulate the function of this device, and hence allows us to design are the following:

$$T = 2\pi\sqrt{\frac{1}{g\left(\frac{1}{R}+\frac{\mu}{x}\right)}} \tag{6}$$

$$K = N\left(\frac{1}{R} + \frac{\mu}{x}\right) \tag{7}$$

$$\vartheta = N\left(\frac{1}{R} + \frac{\mu}{x}\right) \tag{8}$$

As shown in Eq. (6), by having a friction coefficient equal to zero, the period of the system would be exactly equal to the period of a simple pendulum.

In summary, the Pendulum Isolation System corresponds to structure support devices based on the work principles of the simple pendulum, where the oscillation period does not depend on the mass of the system, but only on the radius of curvature of the isolator (analogous to the length of the rope in the case of simple pendulum). The energy dissipation mechanism supplied by this device is generated through the friction between the elements of it.

There are two types of pendulum isolators: single and double concavity isolators. The main advantage of these last is that, by having double concavity, smaller devices can be generated to support the same displacement of a single concavity device.

In Fig. 2.1, a schematic section of a pendulum isolator with single sliding surface is shown, and in Fig. 2.2, a pendulum isolator with double sliding surface is shown. In both cases you can see the spherical surface plate, which serves to slide the "pill" according to the laws outlined above, using the “equivalent” radius of curvature, that is provided by the manufacturer and takes into account the type of the device (with single or double sliding surface). This mechanical system is precisely what is called pendulum isolator. Fig. 3 shows the hysteresis curve associated with this device.

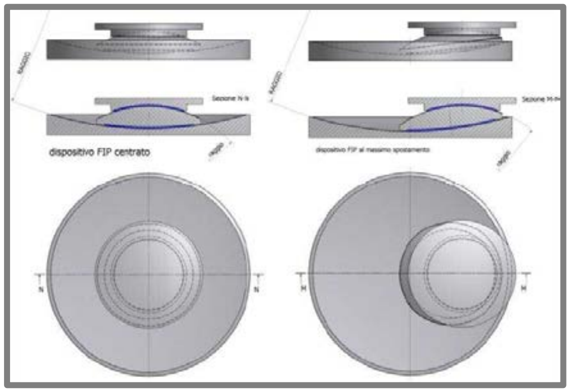

Fig. 2.1 – Schematic Section of a pendulum isolator with single sliding surface

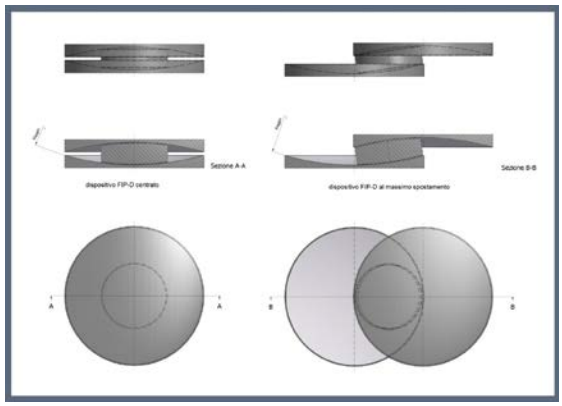

Fig. 2.2 – Schematic Section of of a pendulum isolator with double sliding surface

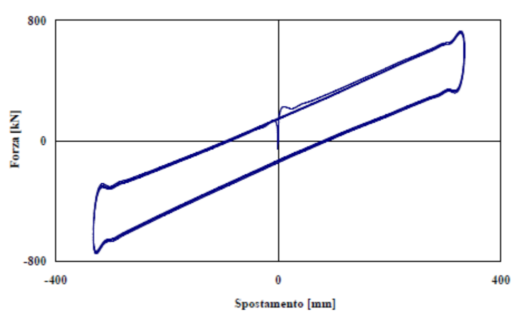

Fig. 3 – Esperimental Hysteresis Curve of a Pendulum Isolator

The invention of this device, and its application to large structures, allow its use in areas where seismic problem is considerable.

3. Pendulum Isolator in Practice

To make a correct analysis of a system incorporating these devices, you must first generate representative numerical models to collect the proposed structuring and then extrapolate to the general system.

As mentioned in the previous chapter, pendulum isolators are isolation systems based on the principle of the forces of the pendulum. Each isolator consists of a contact surface with some degree of friction, coupled with a geometric constitution that provides isolation system, as well as reconstitutives forces and energy dissipation, to the structural system. This system has the advantage that seismic isolation properties of the structure are independent of the mass of the latter. Fig. 4 shows a typical pendulum isolator with double sliding surface.

Pendulum isolator is determined by different parameters such as its friction coefficient, radius of curvature, maximum displacement capacity and maximum axial loads (combined with displacement or at zero displacement that can support. The average axial load during earthquake is used in Eq. (7) and (8). These parameters characterize the behavior of isolators and, therefore, also condition the overall seismic performance of the structure.

However, for this kind of isolators, uprisings are not allowed, i.e., the minimum axial load on the isolators is zero during an earthquake. This clearly proves to be a limitation, especially in relatively slender structures where global rollover on the basis are greater, implying a high risk of lifting. However, tension on isolators is never recommended, even on isolators with some capacity to resist uplift.

Fig. 4 –Pendulum Isolator with double sliding surface

3.1 Aspects of the Analysis with Frictional Isolators

Regulatory requirements of structures analysis with frictional isolators involve an analysis records, also called time-history analysis. For this, the Chilean code allows two alternatives: use at least three seismic records, obtaining acceptable results from the design point of view for the envelope of the analysis; or seven seismic records, obtaining acceptable results from the design point of view for the average analysis (section 8.4.2.1 of the NCh2745 of 2003 standard).

It must be specially verified that no lifting of the isolators occur in any moment of the registration in which it is intended that for an average behavior, isolators do not have any uprising.

In summary, the analysis focuses on finding a spatial distribution and configuration features of each isolator such that can achieve the parameters required for the structure, that is; expected period, desired energy dissipation (usually checked through equivalent viscous damping), maximum displacements, and preventing the lifting of the isolators. In addition, the expected seismic parameters (deformations, vertical forces, etc.) must be within the range accepted by the regulations; in the case of Chile is the NCh2745 of 2003 code.

Seismic records to be used must be natural or artificial records corrected and adjusted to the spectrum of the respective code, which in Chile is NCh2745 of 2003 (section 8.4.2.1 and section 8.6.4.1).

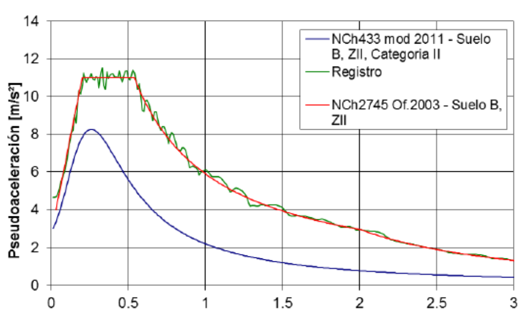

Fig. 5 – Acceleration Spectrum, log 1x, with 5% damping.

For the Chilean legislation is not necessary to use specific records in location (section 6.5.3.3).

For buildings studied, seven records alternative was chosen. Below are exemplary a pair of graphs of time-acceleration each.

• Record 1 (S1)

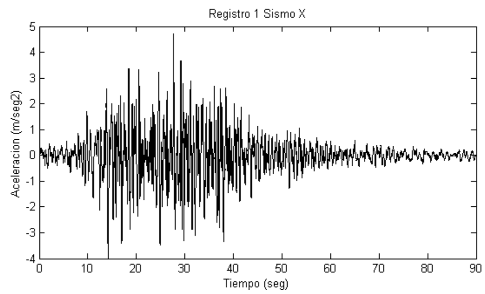

Fig. 6 – X Seismic Record

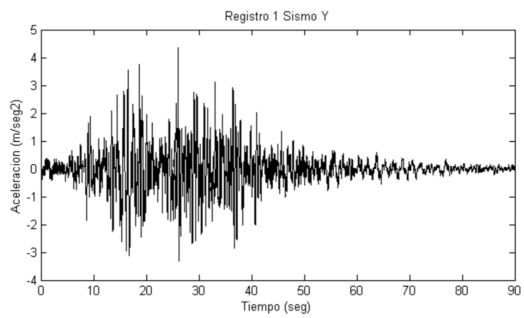

Fig. 7 – Y Seismic Record

For the modeling and analysis, ETABS structural analysis software is used. The isolators are modeled by Links elements with nonlinear properties, which simulate the isolation interface between substructure and superstructure. The modeling of the building isolated in Chile must meet the requirements of section 8.5.2.2 of the NCh2745 of 2003 code.

The analysis with records (time-history) in Chile must comply with the requirements of section 8.6.4 of the NCh2745 of 2003 code.

The analysis of the isolated structure is an iterative process, starting from an initial configuration of displacement and sought global period and equivalent viscous damping. This process ends after displacements of isolators have converged, i.e., the difference between the displacements calculated for the current configuration and displacements of the previous configuration are minors. In addition, you should check that the maximum axial loads on isolators considered in the models do not exceed the limits associated with each isolator. At the same time it is necessary to control that, for each instant of each analyzed log, the maximum displacement of each isolator does not exceed the limits of maximum displacement determined by the particular configuration of each isolator and, also, compare this maximum displacement with minimal deformation, which should be able to take the structure, given by the design displacement (section 7.3.1 and section 7.3.5 of the NCh2745 of 2003 code). The maximum displacement of each isolator is given by:

$$d_{aisl.max} = \sqrt{u_x^2 + u_y^2} \tag{9}$$

Where u_x and u_y are the displacements in the x and y directions respectively (section 8.6.4.2 of the NCh2745 of 2003 code).

The behavior of each isolator must be analyzed in the representative model along each record. For example, Fig 8 shows the displacement along the axis "y" of one of these isolators for S1 Register:

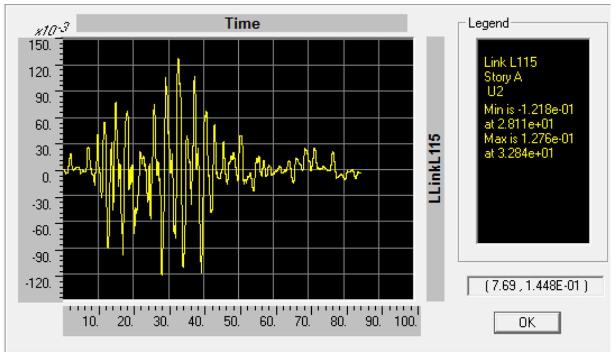

Fig. 8 – Example of Displacement Register according to Axis Y of an isolator

Fig. 9 shows the record of the axial forces of the same isolator for Registration S1. It can be seen that in this case no lifting was found (maximum force equals compression 800t).

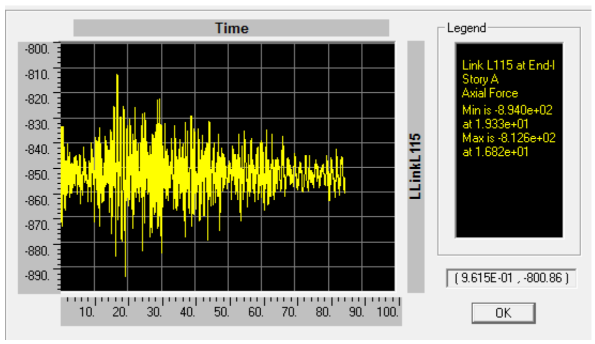

Fig. 9 – Example of Axial Forces Register of an Isolator

For each required verification, different load combinations must be considered, in the case of Chile they are:

▪ For static axial load on each isolator (determinant on the friction of the isolator):

$$N = 1.0 \cdot PP + 0.5 \cdot SC$$

▪ For maximum characteristic load on isolator:

$$V = 1.2 \cdot PP + 0.5 \cdot SC + |E_{\max}|$$

▪ For lifting checking of isolators:

$$L = 0.8 \cdot PP + |E_{\min}|$$

▪ For deformation calculations:

$$Def = 0.8 \cdot PP + |E_{mpos}|$$

Where	PP	Own weight load and other dead loads
	SC	Use Overload
	E	Seismic Action
	E_{mpos}	Seismic Action for the probable maximum case

3.2 Case Study

Here are two examples of application of these devices in Santiago, Chile, which were built after the earthquake of February 27th, 2010.
However, the two of them were activated during the magnitude 8.4 earthquake last August 25th, 2015.

3.2.1 Los Cactus Project – Nueva La Dehesa Building

The first one presented is the Los Cactus project in the commune of Lo Barnechea, in Santiago, which has an exceptional condition, where there are two nearly identical buildings, where one has isolation system and the other one does not. This is, for obvious reasons, very important because it allows comparing not only the issue of response of the structure, but also the economic issue.
The project consists of a reinforced concrete structure, with nine stories high plus four underground, with a total height of 42 m and mixed structure. This is seismically isolated by a pendulum system at a sky level on the first underground (-1 level).

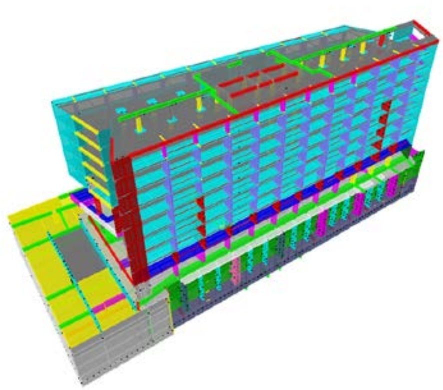

Fig. 10 – ETABS Model of Los Cactus Building

In this case, we analyzed and designed based on double curvature pendulum isolators, with maximum permissible loads between 100 and 1,000 tons, and an average friction coefficient of 3.5%. The building has 42 double curvature pendulum isolators at a first underground sky level, as shown in Fig. 13. The design displacement of the devices is 35 cm.

The distribution of pendulums on first underground plant is shown in Fig. 11.

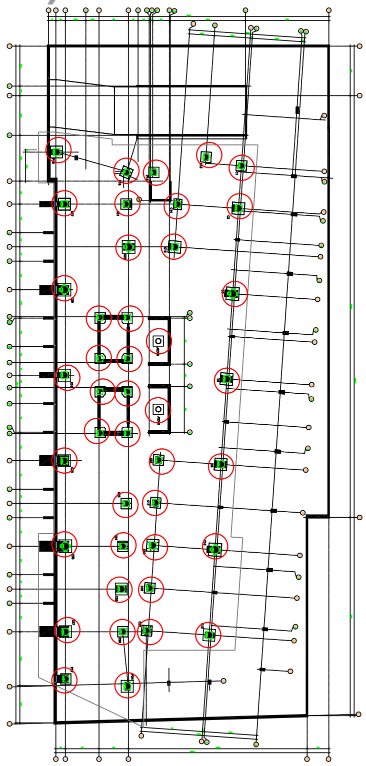

Fig. 11 – Distribution of the isolators on the

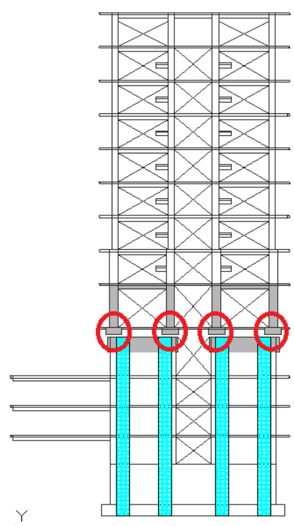

Fig. 12 –elevation of the building.

According to the model shown in Fig. 10, the main period of the building is 2.877 seconds. The equivalent mass of the first three vibration modes is shown in Table 1.

Table 1 – Vibration Modes and Associated Equivalent Mass

Mode	Period [s]	Meq. X	Meq. Y	Meq. Rz
1	2.877	0.006	53.509	5.912
2	2.858	54.75	0.434	5.030
3	2.793	3.703	5.001	31.922

The Building was designed using three different seismic records, as the one shown in Fig. 13.

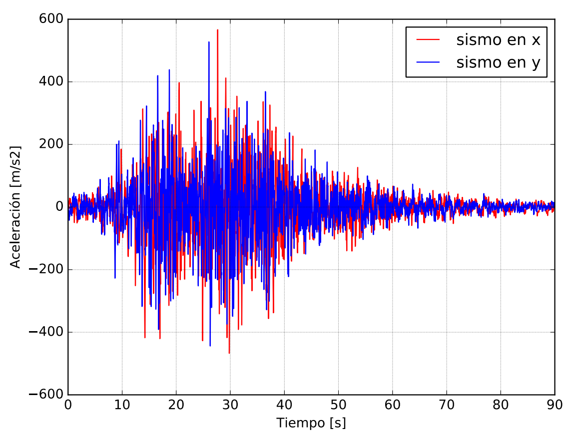

Fig. 13 – Accelerations Record during a Seismic Event

3.2.3 Kennedy Building

The second presented is the Kennedy building. This office building is a reinforced concrete structure, located in Santiago, Chile, with six stories high plus four underground, a total height of 36 m, and mixed structure. This is seismically isolated by pendulum isolation system, located on the sky of the level 1 underground.

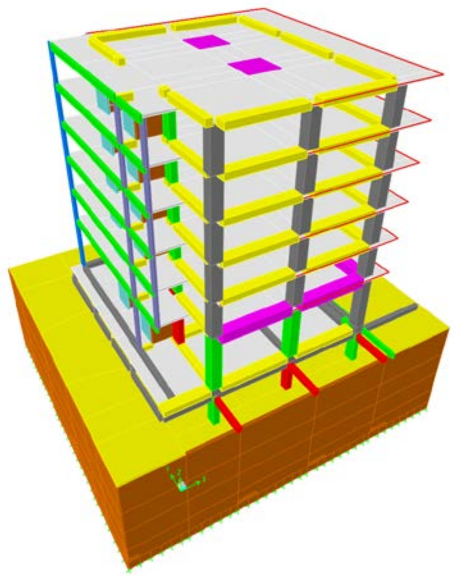

Fig. 14 – ETABS Model of the Kennedy Building

The isolation system of the Kennedy Building was designed based on double curvature pendulum isolators, with maximum permissible loads between 100 and 1,000 tons, and an average friction coefficient of 3.5%. The building has 17 double curvature frictional pendulums, located on the sky of the first underground like the one shown in Fig. 15 and Fig. 16.

The distribution of pendulums on first underground plant is shown in Fig. 15.

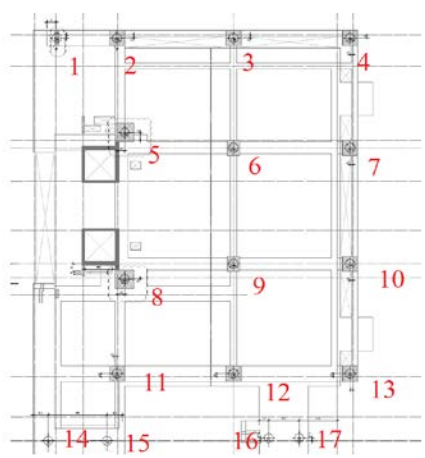

Fig. 15 – Distribution of isolators on the sky plant of first underground.

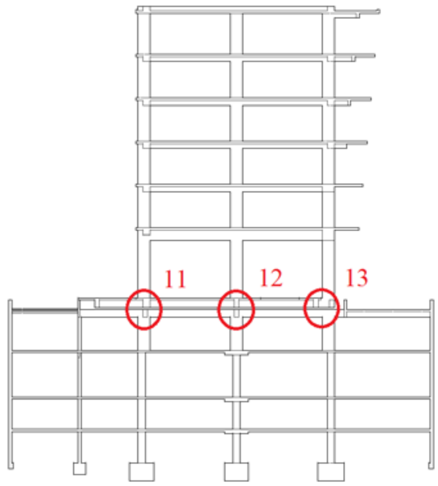

Fig. 16 – Location of the isolation devices in elevation of the Building, according to the numeration of Fig. 15.

According to the model shown in Fig. 14, the main period of the building is 2.963 seconds. The equivalent mass of the first three vibration modes is shown in Table 2.

Table 2 – Vibration Modes and Asociated Equivalent Mass

Mode	Period [s]	Meq. X	Meq. Y	Meq. Rz
1	2.963	51.880	0.000	0.074
2	2.919	0.000	52.065	0.015
3	2.824	0.035	0.019	31.990

The building was designed using seven different seismic records, like the one shown in Fig. 17.

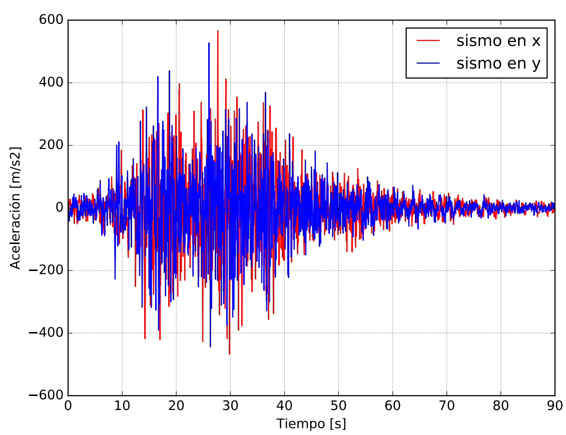

Fig. 17 – Acceleration Record during a Seismic Event

4. Results

During the earthquake occurred in the region of Coquimbo and felt in the central area with a special intensity, none of the buildings reported any damage on nor the structural elements, or secondary elements.

These two projects were analyzed within the regulatory framework of the NCh2745 which became official in 2003 in Chile. These regulations, being the firsts that addressed the seismic isolation issue in Chile, were extremely conservative, which obviously impacted on the associated costs. Notwithstanding the above, an economic comparison in the Los Cactus project was feasible because, as stated are twin buildings, one with and one without isolation system. The economic result was around 3-5% more expensive in the case of the isolated building. Important to mention is the fact that the new code relaxes the conditions for isolated buildings, which means those differences should disappear.
Regarding its dynamics behavior, during the last seismic event, activation of the seismic isolation system was appreciated, being able to visually see a displacement of about 1 cm in all cases.

In particular, in the Los Cactus project, the building without isolation system reported damage in secondary elements, especially in clearing one of its elevators. On the other hand, the isolated building did not report any damage.

5. Conclusions

The use of seismic isolation has been a major breakthrough in the development of structural engineering.

The fact that, in the field of construction, we do not have the real possibility of creating prototypes makes vital the fact of implementing technological elements with controlled fabrication in structures in general, which considerably reduces the uncertainty of our specialty.
In particular, the use of isolators enables to focus the effects of the earthquake on specific elements of known mechanical behavior, and this behavior is particularly true in the case of pendulum isolators, given that well known materials and geometries allow ensuring its response.
It should be noted that the Chilean code does not help to implement the use of these devices because it puts extreme conditions, especially in the light combination. Considering that the isolated building from Los Cactus project was made with the 2003 Chilean code, without incorporating changes from 2009 code, we can see a cost difference from the non-isolated building of approximately 5%. This difference would be considerably diminished if we incorporated the new code changes mentioned before.

6. References

[1] Christopoulos C., Filiatrault A. (2006) *Principles of passive supplemental damping and seismic isolation.* IUSS Press 2006;277-297.

[2] Almazán J. L. (2001) *Torsión accidental y natural de estructuras aisladas con el sistema de péndulo de fricción, Tesis para obtener el título de Doctor en Ciencias de la Ingeniería. Pontificia Universidad Católica de Chile, Santiago de Chile.*

[3] Lee Cl, Chen, Cw, Chung Ll, Wang, Yp. (2006) *Optimal design theories and applications of tuned mass dampers. Engineering Structures*.

[4] EPS (2007) Friction Pendulum Seismic Isolation. Earthquake Protection Systems, Inc. Mare Island, USA

[5] Naeim, F., and Kelly, J., (1999), *Design of Seismic Isolated Structures: From Theory to Practice*, John Wiley & Sons, Inc., New York.

[6] Wilson, E., (2000), *Three Dimensional Static and Dynamic Analysis of Structures*, Computers and Structures, Inc., 3rd edition.

[7] Soong, T., and Dargush, G., (1997), *Passive Energy Dissipation Systems in Structural Engineering*, Wiley.

[8] Norma Chilena 2745 (2013), *Análisis y Diseño de Edificios con Aislación Sísmica*, INN, 2nd edition.