Base isolation for Seismic Retrofitting

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Abstract

The base isolation system is a good solution for the seismic rehabilitation since it has the capacity to eliminate or to reduce fairly structural and non-structural damages. As a measure of reinforcement, it allows to keep the architecture of the building and can be applied without interrupting the activities.

As a retrofit technique, it still raises some questions, mainly in what concerns the insertion of equipment in an existing structure. This question is the focus of the present study.

It is presented a collection of the different procedures that can be adopted in the seismic rehabilitation of buildings with seismic isolation, for different kind of structures: masonry structures, concrete structures and steel structures. Seismic isolation was applied on an existing building, testing some schemes of installation with the objective of evaluating how the insertion of the base isolation devices in the structure interferes in the variation of the efforts on the structural elements.

In conclusion, to optimize the scheme of installation, installing the isolators in the columns that have less vertical displacement should be the first step. To intervene in a uniform way is the most effective way of reducing the variation of efforts.

Key-words: Seismic Rehabilitation, Strategies of Seismic Protection, Isolation Base, Procedures, Installation Sequence, Isolators.

1.Introduction

Base isolation is a system of seismic protection that consists in decoupling the upper level structure from the foundation by inserting a horizontal soft layer.

The above mentioned system reduces the vibration on the structure. The insertion of isolating devices allows the building to remain almost stationary relative to the ground motion, resulting in a drastic reduction in damage to both the structural elements, non-structural elements and building contents (Guisasola & Reboredo, 2017). This measure not only prevents the collapse, but also reduces damage and allows the buildings to keep operational after the occurrence of earthquakes, what can be very important in the case of buildings like emergency centres, fireman headquarters and hospitals (Ferraioli & Mandara, 2017). The immediate consequence is the rise of the fundamental period and, naturally, the decrease of the natural frequency of vibration of the structure, followed by the decrease of the spectral acceleration and, consequently by a reduction of seismic forces in the building (Meireles, 2011). The fundamental frequency of the isolated buildings can be reduced from 1/2 to 1/8 in comparison to fixed structures.

For isolated structures, the structural frequency is shifted away from the predominant frequencies of typical ground motions.

The horizontal movements are concentrated on the system of isolation and the rest of the building behaves like a rigid body. Due to these changes, there’s a new first vibration mode where the structure moves as a rigid body. In this case, the modal participation of the fundamental frequency becomes much more significant than the other vibration modes, giving them a small contribution for the efforts and displacements. The application of the seismic isolation allows to reduce, or even to eliminate the inter-story drift (Mayes & Naeim, 2014). As it can be observed on Figure 1, the displacements increase, but not the deformation.

A B

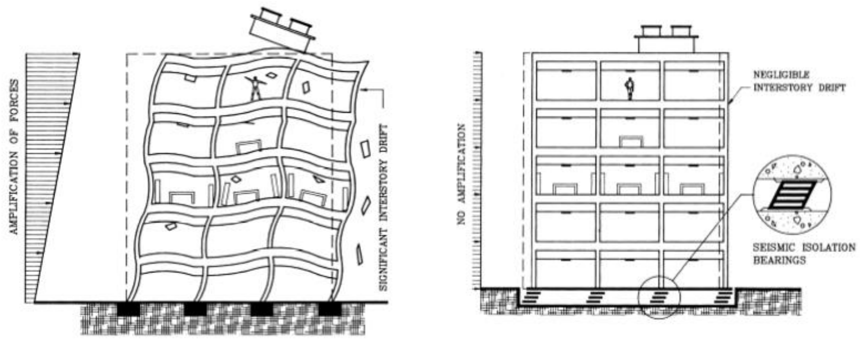

Figure 1 - Modes of deformation of fixed based buildings(A) and based isolated buildings(B) (Mayes & Naeim, 2014)

This aspect is of great importance since the damage that normally occur in the structural and non-structural elements of the fixed based buildings, during an earthquake, are related to the occurrence of inter-storey drifts that causes the cracking of structural elements.

In an isolated structure the lateral drifts are concentrated in the level of the isolated devices. Thus, the structural and non-structural elements will produce smaller efforts than the ones produced if the structure presents a fixed base, and the superstructure will not present considerable damage (Barbat & Bozzo, 1997).

The centre of stiffness of the isolation system is close to the projection of the centre of mass of the building on to the ground plan. The latter minimizes the excitation of torsional vibration of the building on the isolators during an earthquake.

The main types of base isolation systems are the High Damping Rubber Bearing (HDRB), the Lead Rubber Bearing (LRB) and the Friction Pendulum System (FPS) (Guerreiro, 2011). The HDRB is the most commonly adopted base isolation system. It has high damping capacity, horizontal flexibility and high vertical stiffness. Although the HDRB system involves hysteretic dissipation of energy and nonlinear behaviour, it may still be treated as linear, using equivalent stiffness and damping properties (FIP Industriale, 2016).

2. Base Isolation for Seismic Retrofitting

The base isolation can also be applied as seismic retrofitting. This retrofitting strategy has advantages in comparison to the conventional techniques, such as to prevent the collapse and to reduce the possibility of the occurrence of damage. Using this strategy, it is not necessary, after an earthquake, to repair elements of the structure, as it happens when using the conventional techniques.

The works are only at the base level, not being necessary to interrupt any of the functionalities of the structure. Contrary to what happens when applying the other techniques, the execution of retrofitting works doesn't imply an interruption in the activities of the building during a certain period of time. It presents, thus, a great potential to rehabilitate habitation buildings, schools, hospital and bridges. Also the rehabilitation of historical buildings is possible by maintaining the integrity of the building's exterior façade and thus preserving the architectonic patrimony (Matsagar & Jangid, 2008).

The process of implementation of the isolation system on an existing building is considerably different from the implementation on a new one.

In short, it consists in the following phases: in the first phase, it should be taken in account that the base isolation system reduces the seismic forces, but doesn't eliminate them completely, so it's necessary to adjust the isolation system so that the force and the ductility of an existing structure are strong enough to resist to the reduced forces that result from the application of the isolation. In the second phase, it should be defined the appropriate level for the isolation plan, choosing the one that might be the most beneficial, as for example, the use of a basement. Next, the characteristics of the isolation system should be defined and the equipment should be chosen. In the third phase, the choice of the procedure of the installation of the equipment is made, depending on the type of structure where the intervention will be made. The structures are divided essentially in two types, masonry and concrete. This kind of retrofitting can also be applied in steel structures, once the used procedures are similar to the procedures used in the structures of reinforced concrete. At last, the procedures of the installation of the equipment for each kind of structure will be presented. In (Duarte, 2017), can be found in detail other possible procedures.

Procedures for masonry structures

Structures constructed of masonry in stone or brick using lime or cement mortars transmit their self weight to the ground through masonry walls. While incorporating the seismic isolators, underpinning is done to provide temporary supports along the masonry wall to stop the collapse of the masonry wall. The most usual technique for this type of structure is progressively make openings in the wall to place the base isolators and at the same time build a beam

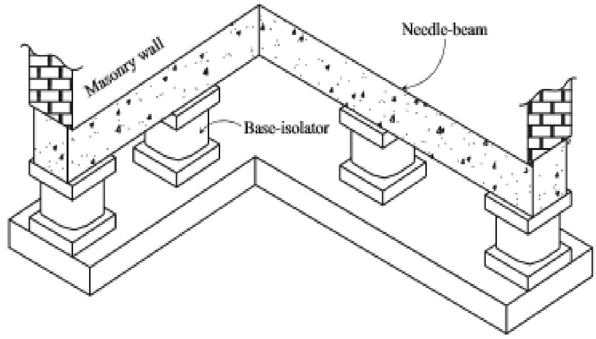

Figure 2 - Base islolation in mansory structure (Matsagar & Jangid, 2008)

mounted over the seismic basic isolators and below the masonry wall. Then, the temporary supports are removed, transferring the vertical load of the structure towards the foundation through the beam and the base isolators (Matsagar & Jangid, 2008).

There are other different procedures to retrofit masonry structures. One of them is the intervention made at the level of the foundations. This implies the construction of sub-foundations. Other procedure that we can follow is inserting the isolation devices in the columns.

Procedures for concrete structures

In the case of concrete structures constituted by beams and columns, the best place to put the isolation devices is near the column-foundation junction. This is possible if an additional floor is created. For that, first it is necessary to cut the column to make enough room to insert the devices and then build a base raft, as can be observed on Figure 3. A more usual alternative consists in using the isolation layer at the first story and place the base isolators at the top of the first story columns. Note that placing the isolation layer in the first floor is less effective as compared to the case in which the base isolators are placed at the ground level.

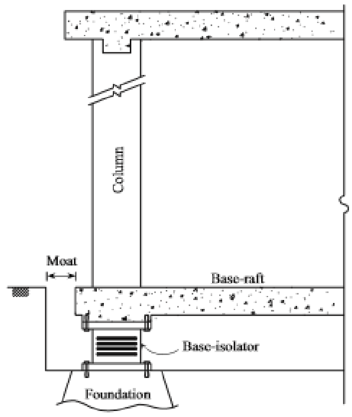

Figure 3 - Base islolation in concrete structure (Matsagar & Jangid, 2008)

The techniques that are used for Base Isolation for Seismic Retrofitting in reinforced concrete structures can be divided in two. The first is called column cut and consists in making a cut at the top of the column to put there the base isolators. The other technique is called lift up and intervenes at the level of the foundations and consists in separating the structure of the foundations, involving the need to build a new slab above the base isolators (Matsagar & Jangid, 2008).

3. Practical Case

A practical case that consisted in the proposal of the elaboration of a seismic rehabilitation using the base isolation as a technique was developed with the model oh the “Laboratório Regional de Veterenária dos Açores (LRVA). This proposal includes the design of the base isolators and the definition of the sequence by which they are inserted in the structure.

First, the structure of the LRVA with fixed base was considered. For that, it was used the computational model of the building, modelled in SAP2000 (CSI, 2016) with fixed bearings.

From the modal analysis of the fixed based structure result the vibration modes represented on Figure 4 and the frequency of vibration, periods and the total of modal participation that are presented on Table 1.

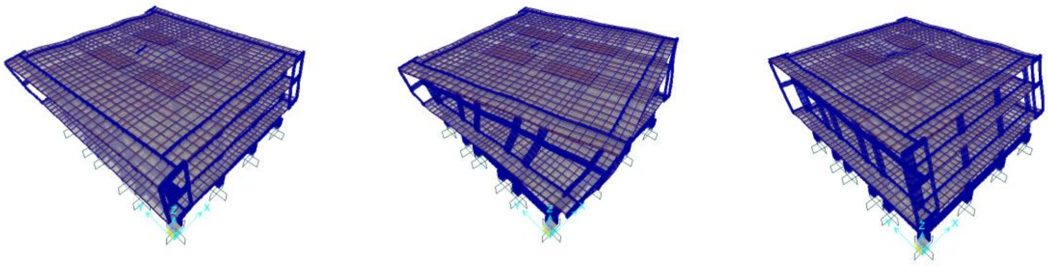

Figure 4 – Vibration modes (Fixed Base)

Table 1 – Modal Analysis Results (Fixed Base)

Modes	Frequency [Hz]	Period [s]	$\sum Ux$	$\sum Uy$
1	2,06	0,486	0,52	0,00
2	2,28	0,439	0,54	0,01
3	2,66	0,375	0,54	0,53
4	7,25	0,138	0,63	0,53
5	7,54	0,133	0,67	0,53
6	7,64	0,131	0,67	0,53

Two aspects are highlighted: the fact that the structure presents a high natural frequency for the kind of building and second the vibration mode is a torsion mode. The method chosen for the intervention was the application of a base isolation system composed by elastomeric bearings of the kind HDRB. The bearings were placed between the ground floor and the foundation where there are square columns with 1 m of side and 1,5 m of height, considering that this is the most appropriate place to install the equipment.

Design of the base isolators

First, the fundamental frequency of the structure of the isolated base was defined from the natural frequency of the model of the fixed base and from the following relation:

$$\frac{f_{fixed}}{f_{isolated}} = 4 \Leftrightarrow \frac{2{,}06}{f_{isolated}} = 4 \Leftrightarrow f_{isolated} = \frac{2{,}06}{4} = 0{,}515 \text{ Hz} \tag{1}$$

We assume a value of 0.5 Hz. It is confirmed that it respects the interval delimited by EC8 (CEN, 2010).

From the aimed fundamental frequency, it is defined the value of horizontal and total stiffness, K_h, of the isolated system that will be divided by the horizontal stiffness of each of the support bearings. Once it's about an equipment of the HBRD type, its behaviour can be simulated through a linear model equivalent and a linear simplified analysis can be used. Thus, the effective horizontal stiffness of the isolation system can be defined by the following expression, that depends on the frequency of the system isolation and the total mass of the superstructure.

$$T_{eff} = 2\,\pi\,\sqrt{\frac{M}{K_{eff}}} \Leftrightarrow \frac{1}{f_{isol}} = 2\,\pi\,\sqrt{\frac{M}{K_{eff}}} \Leftrightarrow K_{eff} = (\,2\,\pi\,f_{isol})^2\,M = (\,2\,\pi\,\times 0{,}5\,)^2 \times 3849{,}32 = 7991{,}27\ \mathrm{kN/m} \quad (2)$$

The second criteria of selection is related to the maximum displacement that can be calculated by the expression:

$$d_{dc} = \frac{M\,S_e(T_{eff}, \xi_{eff})}{K_{eff,min}} \quad (3)$$

The expression depends on the value of the spectral acceleration. To obtain this value, the values of the spectral accelerations were taken from the SAP2000 program for a damping of 12% of each of the 7 accelerograms used in the definition of the seismic action (zone 1.3 and 2.3(Lisbon), for seismic action of type 1 and 2, respectively, and ground, type B. Next, the media of these values was considered, and a response spectrum was made. From this spectrum the value of the spectral acceleration corresponding to the frequency of 0,5 Hz was obtained. It results the value of:

$$S_e(f_{isol} = 0{,}5\,, \xi_{eff} = 12\%) = 1{,}1\ \mathrm{m/s^2} \quad (4)$$

Having all the parameters defined, the calculation of the displacement was made, as it can be seen in the following:

$$d_{dc} = \frac{M\,S_e(T_{eff},\xi_{eff})}{K_{eff,min}} \Leftrightarrow d_{dc} = \frac{3849{,}32\ \times 1{,}1}{37991{,}27} = 0.1115\ \mathrm{m} = 111.5\ \mathrm{mm} \quad (5)$$

The last criteria is related to the capacity of the vertical load of each device. It was used the combination of actions for seismic design situations according to the EN 1990:2002, §6.4.3.4.(6.12b):

Defined those three characteristics, the isolation devices were chosen. For that, the catalogue of the elastomeric bearing of the company FIP Industriale was used (FIP Industriale, 2016).

On table 5 the chosen devices and their capacity of vertical load and stiffness are presented. On Image 5 the geometric arrangement of the devices can be observed.

Table 2 – Base isolation devices

n	Devices	N [kN]	d [mm]	K_e [kN/mm]	n × Ke [kN/mm]	K_v [Kn/mm]
2	SI - N 1000/140	15350	250	4,49	8,98	4000
2	SI - S 1200 /144	12850	250	3,14	6,28	4013
12	SI - S 600/104	2230	200	1,09	13,08	1313
6	SI - S 650/108	2760	200	1,23	7,38	1424
6	SI - S 700/100	3110	200	1,54	9,24	1722
				n $\sum K_e$ =	44,96	

Table legend:

n, number of isolation devices used;

N, axial effort for the combination of the seismic action;

d, maximum displacement;

K_e, effective horizontal stiffness.

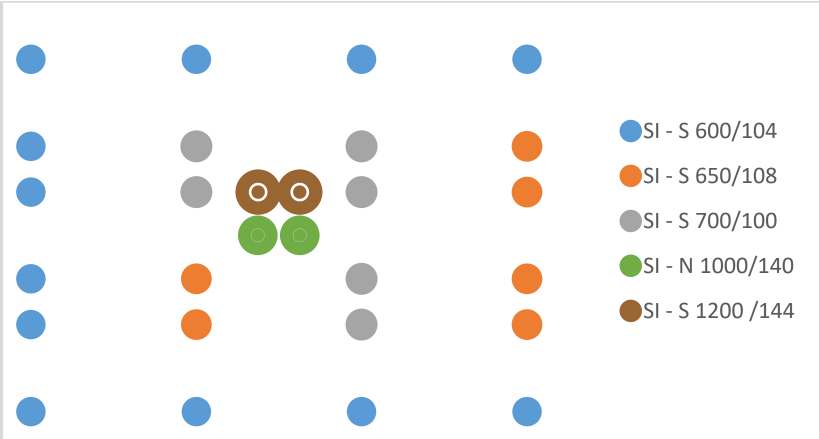

Figure 5 - Geometric distribution of the base isolator devices types

Installation sequence of the base isolators

It's important to create an installation procedure where it is defined the sequence by which the base isolators are placed in the structure. Note that the replacement of a concrete column by a base isolator, due to the difference of stiffness between these elements, may cause a settlement that induces a variety of forces in the elements. Once you can't insert all the equipment at the same time, this situation is worsened by the fact that there are different phases in the process of installation where the structure is supported by concrete pillars and by isolation bearings. This variation of forces can surpass the resistant capacity of certain elements, causing damage. This is the main concern in the installation in phases of the base isolators, so the criteria for the definition of the installation sequence was the minimization of the variety of forces.

In the present study, several hypothesis of possible ways of incorporating the base isolation devices in the structure were tested and the consequences in the variation of the moments in the beams of the first floor were analysed. It was chosen the hypothesis that better respects the criteria mentioned above. For each intervention, the columns that presented less values of vertical displacement were chosen first. In the case of the existence of columns with the same displacement, the following hypothesis were tested:

i) Give priority to the columns with less axial force;
ii) Give importance to the placement of the base isolation devices; this is, trying that each phase is confined to a certain area, acting in columns that are close to each other.
iii) Place 4 or 5 devices in each intervention.

When testing the hypothesis mentioned above, it was possible to gather a group of avoidable situations and select the best ways to incorporate the equipment.

The first complete installation scheme is shown on Figure 6.

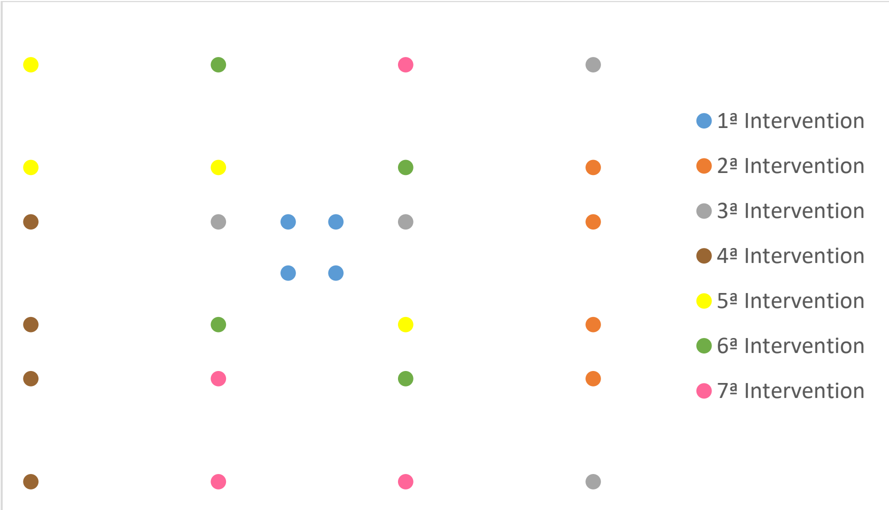

Figure 6 – First installation sequence

In the study of the best installation sequence, the scenarios that happened and the conclusions drawn were:

- In the presence of equipment with the same values of vertical displacement, to choose between the columns that presented the normal force and the ones which would make the arrangement more uniform, the second choice was the most practicable.
- The placement of only one device in the end of a small beam causes a very big variation of movements on the other end of the beam, but if it's possible to place the two devices in the same intervention, the variation of forces is small. For a larger beam, there are no differences between these two choices, once the difference in the amplitude of the moment between the two choices is very small.
- Comparing the hypothesis of placing five devices in one intervention, instead of four, with the hypothesis of choosing the columns that presented an axial effort or the columns that will make the arrangement more uniform, the latter wasn't the most favourable. It can be concluded that the option of placing five devices instead of four doesn't bring any advantage. Besides, the more supports are placed in an intervention, larger is the number of beams to present variation of moments.

The diagrams of the moments about the tested hypothesis that allowed to draw these conclusions are illustrated in (Duarte, 2017).

Hereupon, the optimization of the sequence of installation was implemented based on the conclusions drawn with the previous study. The new sequence of installation was refined according to the following aspects:

i) Start to intervene in the set of columns that present a lower vertical displacement in total;
ii) In the small beams place two supports in the same intervention;
iii) Define the proper number for the quantity of devices to be placed in the same intervention;
iv) Choose the most uniform possible sequence of installation in which the interventions are made in adjacent columns.

Taking in account the conclusions previously drawn, the optimized solution for the sequence of installation is the one presented on Figure 7.

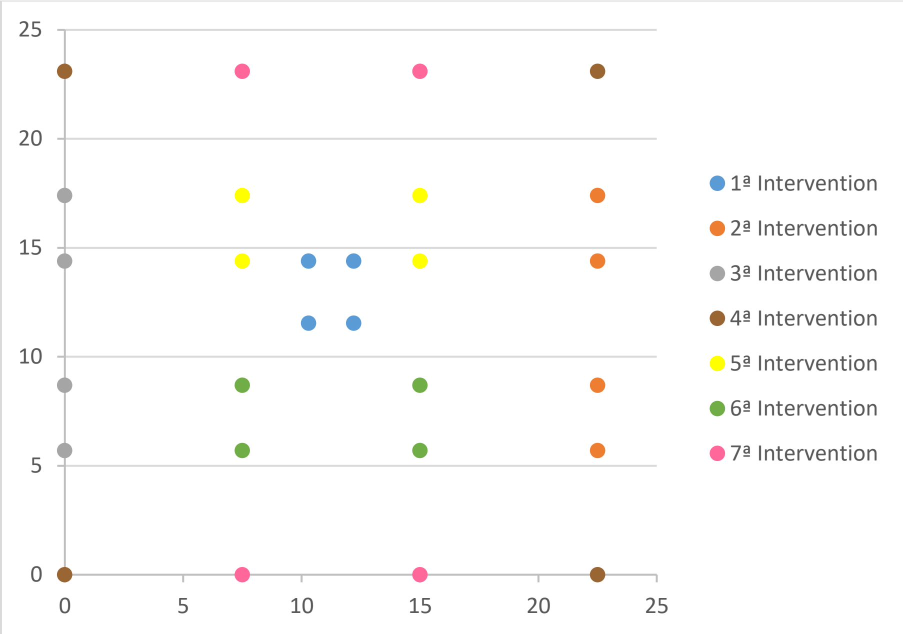

Figure 7 - Second installation sequence

The differences between the two sequences of installation are classified in six sets:

1- Beams where a reduction of the variation was observed.
2- Small beams that increased. Taking in account that one of the concerns of the optimization of the sequence of installation was to place always the two devices in small beams in the same intervention, there were no more situations in which the moment would increase too much in one of the ends.
3- Beams that kept the same variation of moments, but a more uniform behaviour, with less variations among interventions.
4- Beams that kept the same behaviour, but changed the intervention order.
5- Beams that didn´t have any change. Note that those beams have already shown a good behaviour in the first installation.
6- Beams whose behaviour worsened because the placement of the two supports in the ends of the were made in the same intervention and now the supports are placed in different interventions.

For a better undestanding of these differences, consult (Duarte, 2017).

In general, there was a great improvement what justifies the study of the sequence of installation. With the optimization of the sequence of the installation, it is still observed a standard behaviour when the supports are placed in different interventions. This standard consists in the following, when a support is placed in one end of the beam the moments increase on the other end and when the other support is placed, they stabilize. The only way to avoid this behaviour would be to put two devices in the same intervention. However, it’s not possible to do this in all situations, because all the building should be intervened at the same time. Once, this behaviour is unavoidable, a more uniform sequence of installation allows to reduce the number of cases where this happens.

After the insertion of all the base isolation devices, a modal analyses of the structure with isolated base was made. Its fundamental frequency became 0,53 HZ, with the first mode of vibration in X and with a modal participation of 94% in x.

Although the resistant capacity of the beams by the variation of the moments that they suffer while the installation of the devices is not known, it can be detected which beams will need a structural reinforcement. In most of the situations the reinforcement needed in not related to the final situation, but to the intermediate situation. Since these phases are not avoidable because it´s not possible to lift a building as a whole, the way to reduce the number of elements to be reinforced is to choose a sequence of installation that reduces those effects.

4. Conclusions

The insertion of a system of base isolation as seismic retrofitting is different from the application of this technique in a new building. The great difference lies in the procedure to adopt to make the intervention, once this is directly related to the kind of structure (masonry, reinforced concrete or steel structures).

Having defined the procedure to adopt, the concern is defining the best sequence of installation that leads to less variation of forces in the structural elements while the insertion of the equipment. For a better understanding of this subject several possible choices of installation of the system were studied, having drawn the following conclusions:

- There’s a standard behaviour when the base isolators are placed in the end of the beams in different interventions. When the base isolator is placed in one end of the beam, the movements increase greatly in the other end and when the other base isolator is inserted, the movements tend to return to the initial situation.
- The placement of only one base isolator in a small beam for intervention causes a great variation of movements. If two base isolators are placed in the same intervention, the variation is softer. These variations are not so great for a bigger beam.
- The bigger the number of base isolators for intervention, bigger is the number of structural elements to have force variations.
- In doubt between intervene in a pillar with lower effort or in a pillar that makes the distribution of the equipment more uniform, the second choice was the most satisfactory,
- The insertion of base isolators in an irregular way is the greatest cause of forces variation.

Taking these examples as avoidable scenarios, an optimized installation sequence was implemented, where a reduction in the variation of forces in global was observed. However, in certain cases, the standard behaviour is unavoidable, being necessary to reinforce the beams, not due to the final situation, but due to intermediate intervention situations.

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