Design and Optimization of Base Isolated Masonry Buildings

P. Clemente
ENEA, Casaccia Research Centre, Rome, Italy

F. Bontempi
Sapienza Università di Roma, Rome, Italy

A. Boccamazzo
ENEA & Sapienza Università di Roma, Rome, Italy

ABSTRACT:
Masonry can guarantee a very long durability and also a better performance in terms of energy efficiency, especially in cold climate. It is apparent that seismic isolation can contribute to soften the disadvantages that characterize the use of masonry in comparison to framed buildings. Actually, the number of seismic isolated buildings is increasing all over the world, especially where the seismic hazard is very high. Most of them were already tested by even very strong earthquakes and, in general, they showed a very good seismic performance. In this paper the application of base isolation in masonry buildings is discussed. The possible solutions are first analyzed, then the design and optimization criteria are proposed. With reference to a case study, the comparison between a fixed base building and the corresponding seismic isolated building is performed. Two kinds of masonry were considered: brick and *poroton* masonry. The results of a numerical investigation allow to state the suitability of base isolation for masonry buildings in seismic areas also from the economical point of view.

Keywords: Seismic isolation, masonry buildings, economical aspects.

1. INTRODUCTION

Brick masonry can guarantee a very long durability, certified by several ancient constructions, survived up to our age, and a better performance in terms of energy efficiency in cold climate but also for the refreshing during the summer. On the other hands, other materials, such as steel and reinforced concrete, present some advantages with respect to masonry: they allow to build taller buildings, especially in seismic areas; they can guarantee a very low interference of the structural elements with the architectural design; they allowed to realize wider openings, both in internal and external walls, whose position is influenced very few by the structural elements.

It is apparent that seismic isolation can contribute to improve the performance of masonry buildings. As well known, seismic isolation is based on a terrific reduction of the seismic actions, which affect the structure, instead of relying on its strength. This result is obtained by increasing the fundamental period of vibration of the building, so that it becomes less vulnerable to earthquakes. The effects of the lowering in seismic actions were already discussed in previous different papers (Buffarini et al. 2007, Clemente & Buffarini 2008, Clemente & Buffarini 2010) with reference to the Italian Technical Code. This allows accounting for the reduction of the seismic effects in the superstructure, which will be loaded by low actions thanks to the filtering of the seismic isolation system.

In this paper the application of base isolation to masonry buildings is analyzed. The possible solutions are first selected, and then design and optimization criteria are proposed. Finally the results of a comprehensive numerical investigation are shown, which allow stating the suitability of base isolation for masonry buildings in seismic areas, also from the economical point of view.

2. RECENT APPLICATIONS

Seismic isolation was already used in masonry buildings in several cases. One of the most interesting recent applications in Italy, was the base isolated masonry building in Corciano (Fig. 2.1a). It is composed by two blocks, of two and four levels, respectively. The isolation system is made of 18 elastomeric isolators (diameter 500 *mm*), place between the foundation and the superstructure (Di Fusco et al. 2010, Parducci 2010). The structure is in reinforced masonry, with lightened bricks, because at the time of construction the existing Italian code did not allow the construction of four level buildings with normal masonry in high intensity seismic area. Now, with the last code it would be possible to use normal masonry as well.

Several applications have also been realized in China, where base-isolated reinforced brick masonry buildings, with reinforced concrete floors, are being widely used. In particular 5- to 8-story buildings were realized in urban areas (Fig. 2.1b). They have rectangular plan shapes and respected specific design rules. For example, one window of 1.80 *m* width and 1.50 *m* height was realized in each 3.10 *m* length of outside walls. Besides, one or two doors, each with 0.90 *m* width and 2.10 *m* height, are in each 3.30 *m* length of inside walls. The overall windows and doors areas are about 26% of the overall wall surface area (Zhou et al., 2011).

It is worth reminding also the very good performance of a base isolated masonry building in Wenchuan, Cina, which suffered no damages after the earthquake of May 12th, 2008 (Martelli & Forni, 2010). Finally, a new masonry building is being erected in Sulmona, in the framework of a collaboration between ENEA and ANDIL (the Italian association of brick manufacturers), which will be also characterized by a very high performance in terms of energy efficiency.

(a) (b)

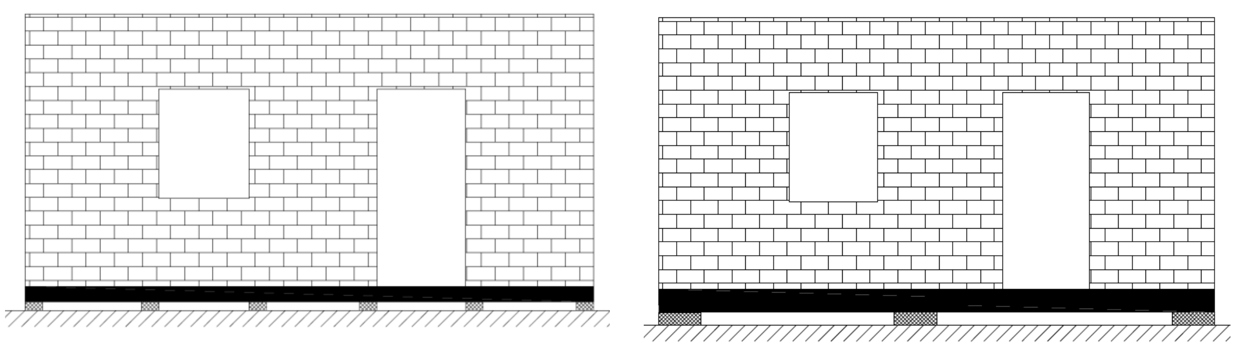
Figure 2.1. Base isolated masonry building (a) in Italy (Corciano) and (b) in China

3. BASIC CONCEPTS

Use of base isolation in masonry buildings is conceptually incorrect. In fact, masonry walls transfer loads to the foundation along their entire length, while the isolators represent a discretization of this continuous support (Clemente et al., 2012). On the other hand, the stiffness of masonry buildings is very suitable for the application of seismic isolation, because it guarantees the needed decoupling between the motion of the building and that of the soil.

A first solution for the insertion of seismic isolators is based on the consideration that each portion of masonry wall, contained between two openings, should transfer to the foundation a vertical force, a horizontal force and a bending moment (Fig. 3.1a). As a result at least two supports should be placed at its base, preferably at the boundary of the wall, in order to lower, as much as we can, the actions due to the bending moment. In order to avoid dangerous concentrations of shear stresses in masonry, both the two bearings should be able to support horizontal actions. Obviously, a suitable horizontal beam is always necessary above the isolation system, which should be able to transfer the shear forces from the superstructures to the elastomeric isolators. This solution could be very expensive, because it requires a large number of devices and is not very suitable for short walls. Specific devices should be designed to optimize this solution and to make it competitive with the others. Besides, each isolation device could have a quite low compression load, which could be lower than the tensile load induced by the seismic actions. As a result the devices should be able to support traction.

The alternative is to realize a very rigid structure under the walls of the first level, which should be able to absorb all the local actions from the superstructure and to transfer them to a limited number of devices, placed at the wall crossings (Fig. 3.1b). This solution appears to be more suitable for a wide application of base isolation in masonry buildings. In practice the rigid structure under the first level is made of reinforced concrete and so are the foundations.



(a) (b)

Figure 3.1. (a) Each masonry wall has at least two bearing, (b) isolator devices are at the wall crossings

Another important issue is the position of the isolation devices. It is worth pointing out that, in the case of base isolated buildings, a rigid deck is necessary just above the isolation level and the foundations are at a lower level in comparison with the corresponding fixed base building, due to the presence of the isolation system. The height of this gap should allow the inspection of the isolators and their replacement, in case of damage. For this last reason the realization of an underground level could be suitable. It allows a safe inspection of the isolation devices and can be used as parking place or other.

Usually the isolation devices are at the top of the underground level (Fig. 3.2a). Actually, from a structural point of view, they can also be at an intermediate height or at the bottom of this level. The only requirement is that the structural elements between them and the first deck should be rigid enough in comparison with the devices themselves. It is important to point out that in this case the walls of the underground level will be movable with reference to the floor below them and, consequently, a gap is needed to absorb these relative displacement, which makes not usable the space close to the walls (Fig. 3.2b). As a result, the surface of the underground level, which can be used, is lower and the gap interests the underground level for its entire height. For these reasons the solution with devices at the top of the underground level should be preferred.

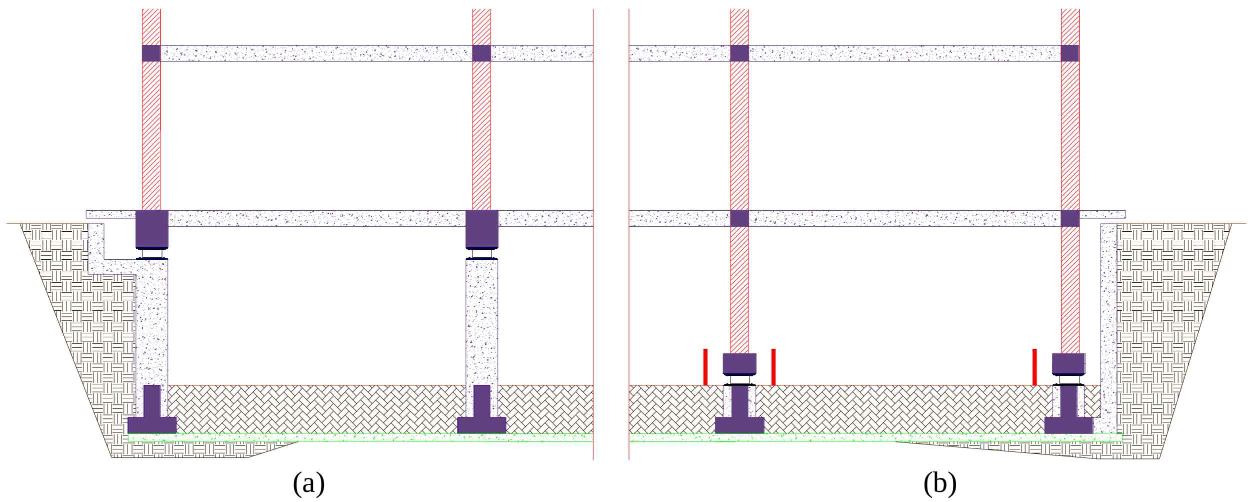


Figure 3.2. Isolation system (a) at the top and (b) at the base of the underground level

4. DESIGN AND OPTIMIZATION

The economic suitability of seismic isolation depends on several factors (Clemente & Buffarini, 2010), such as the earthquake intensity, the soil characteristics, the shape and the size of the building.

General considerations, valid for all the structures, cannot be stated, so in order to point out the main aspects of the comparison, refer to the building in Fig. 4.1. It has a very regular shape in both plan and elevation: this guarantees a good validity of the considerations one can deduce from this study. Besides, it is not difficult to design a seismic resistant structure for it with traditional techniques, and it is allowed using simplified criteria for the design. The two cases of fixed base building and seismic isolated building were considered.

Two kinds of masonry have been considered, having the following mechanical characteristics:

- brick masonry (B): f_k= 12 *MPa*, f_{Vk0}=0.3 *MPa*; *E*= 12000 *MPa*, γ= *2000* kg/m^3;

- p*oroton* masonry (P): f_k= 5 *MPa*, f_{Vk0}=0.2 *MPa*; *E*= 5000 *MPa*, γ= *1600 kg/m³*, which is obtained adding light materials during the production; this resulted in the reduction of the weight and of the thermal conductivity.

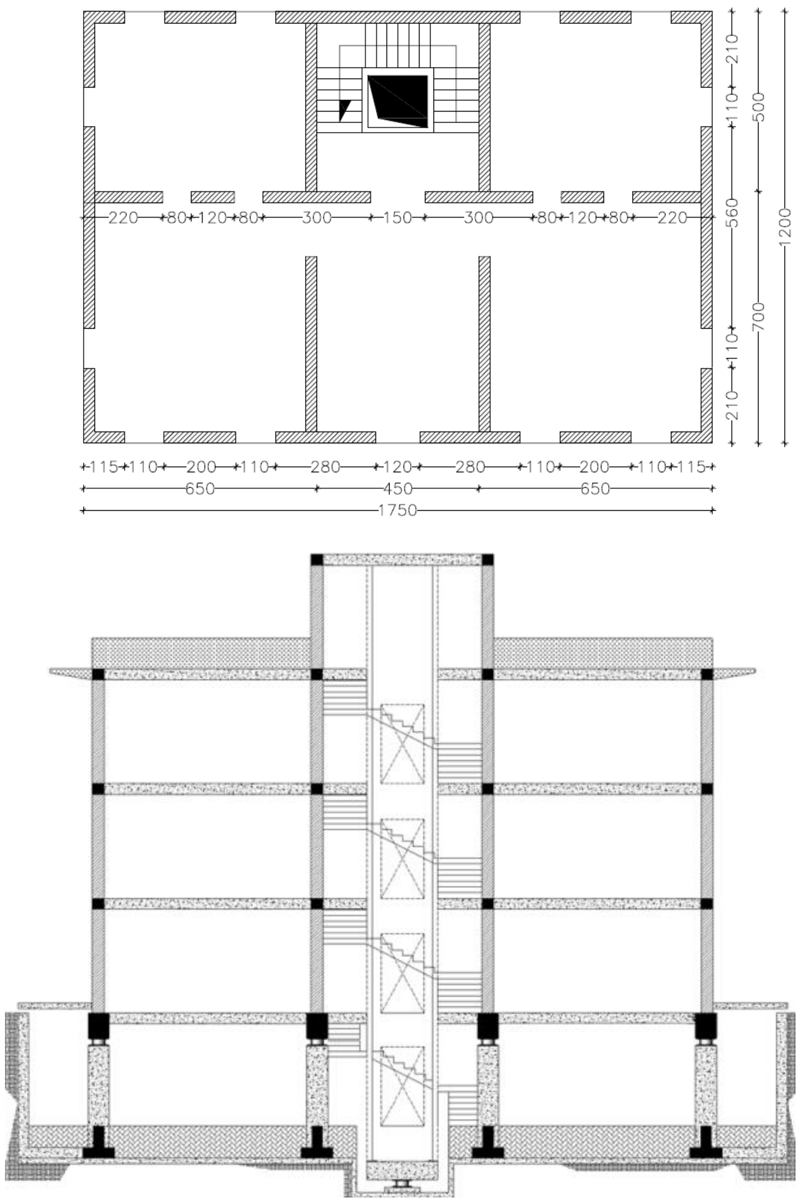


Figure 4.1. Case study: typical level plan and vertical section

All the decks have a thickness of 25 *cm*, and are rigid enough to ensure a suitable distribution of the seismic actions among the walls at each level. The buildings have been designed following the design criteria for "simple buildings" given by the Italian Technical Code. The structure is subject to the usual permanent loads (self weight and other permanent loads) and to the typical variable loads of the residential buildings (2.0 kN/m^2). The foundations are composed by a grid of concrete beams, placed under the masonry walls, and designed to show an elastic behaviour, even under seismic actions. A framed concrete structure is designed, with beams under the masonry walls and columns at the wall crossings. These columns are large enough to contain the isolation devices. The foundation structure was designed for the isolated case and then adapted to the fixed base one.

5. DESIGN OF BASE ISOLATED MASONRY BUILDINGS

In order to compare the base isolated solution with the fixed base one, the structural design was carried out by referring to the Italian Technical Code, in both cases of fixed base and seismic isolated buildings (Boccamazzo, 2010). For the fixed base building the cost analysis with increasing seismic intensity was first carried out. In order to compare these with the costs of the corresponding isolated building, three seismicity level were selected, corresponding to high, medium and low seismicity area, respectively. The cost obtained are reported later in Tab. 6.1. The values are normalized with reference to the cost of a fixed base building in high seismicity area, which has been assumed unitary.

The same buildings (cases *B* and *P*) were designed with an isolation system (*is*), placed under the first deck. Elastomeric devices (*HDRB*) and sliding isolators (*SD*) were used. For the isolated solution the spectral value $S_{d,is}$ for the design of the superstructure was first fixed. The choice of $S_{d,is}$ depends on economic evaluations. In fact, from a comprehensive numerical investigation, it was very apparent that the cost gets up for $a_g{\cdot}S \geq 0.2g$. So this value seemed to be the most appropriate one for the superstructure. In Tab. 6.1 the costs of the superstructure are shown in the two cases *B* and *P*.

It is worth reminding that for the superstructure of seismic isolated buildings a structural factor q_{is} = 1.5 is usually allowed, so the corresponding elastic spectral amplitude is $S_{e,is} = q_{is}{\cdot}S_{d,is}$. The period T_{is}, which corresponds to $S_{e,is}$ in the elastic spectrum for the isolated structure, is the period that must be used for the design of the isolation system.

The set of elastomeric isolators used was defined in a previous paper according to ISO code (2007), as well as the fundamental criteria for the design and check of the devices (Clemente & Buffarini, 2010). These were chosen on the basis of the period T_{is}, which corresponds to the maximum acceleration $S_{d,is} = 0.2g$ in the building, previously defined as the optimum value. Obviously, the corresponding value T_{is} depends on the shape and amplitude of the spectrum. In the analysis the usual spectral shape has been considered, with T_B = 0.15 *s* and T_D = 2.5 *s*, while T_C was assumed equal to 0.40, 0.50 and 0.80 *s* for hard, medium and soft soil, respectively.

As already said, three values of $a_g{\cdot}S$ have been considered, equal to 0.25*g*, 0.35*g* and 0.45*g*, respectively, and corresponding to low, medium and high seismicity area. For each of them the three spectral shapes before defined have been considered. The corresponding spectral amplitudes, which affect the fixed base buildings in low, medium and high seismicity areas, respectively, were deduced assuming the amplification factor F_0 = 2.5 and the damping ratio ξ = 5%.

For each case, the design period of the isolated building is obtained from the corresponding elastic spectrum, plotted for a damping ratio ξ = 15%. It is the value T_{is} of the period at which the design spectrum amplitude is equal to 0.2*g*. The obtained values for the period are in Tab. 5.1. In any case the minimum value of 2.0 *s* has been assumed, in order to guarantee a suitable decoupling between the soil and the structure vibrations. For any found T_{is}, the total stiffness K_{esi} can be evaluated, the total mass of the superstructure being known with a sufficient accuracy.

The design of the seismic isolation system has been performed according to the usual suggestions. The devices have been put under the crossing between the walls and at least eight of them are elastomeric isolators, which have been mainly deployed under the perimeter walls. Besides, only one type of elastomeric isolator and one type of sliding device have been used.

Table 5.1. Period of the isolated buildings

$a_g \cdot S$	*0.25g*	*0.35g*	*0.45g*
	$T_{is,3}$	$T_{is,2}$	$T_{is,1}$
Hard Soil	*2.0*	2.0	2.2
Medium Soil	*2.0*	2.0	2.6
Soft Soil	*2.0*	2.8	3.3

Several deployments have been considered, which comply with the previous requirements and for which the dynamic behaviour is optimum. This is very simple for the considered building and in the case of only one type of elastomeric isolator. For each deployment, the following steps have been done:

1. the stiffness K_e of the single device has been deduced, just dividing K_{esi} for the total number of elastomeric isolators, which in this case is the same for the two deployments;

2. the building being very regular, a first but well approximated value of the design displacement can be deduced on the basis of the spectral displacement and of the rotational stiffness of the isolation system, which influences the displacement due to the additional eccentricity (5% of the corresponding length of the building);

3. with K_e and the value of the design displacement, the isolator to be used can be chosen in the defined set, and then the vertical load can be verified.

Finally, the deployment in Fig. 5.1 was selected. The characteristics of the elastomeric isolators and the sliding devices corresponding to the selected deployment are summarized in Tab. 5.2. The *HDRB* are individualized by means of the number of devices used, the diameter D, the thickness of the single rubber layer t_i and the number of rubber layers n_g; the shear modulus is always $G = 0.8$ *MPa*. The Sliding Devices are individualized by mean of the number of devices used, the maximum vertical load V and the maximum displacement d_2.

The comparison between the different solutions is performed on the basis of economical considerations. According to a proposal consistent with the official prize list used, the cost per unit volume of the elastomeric isolators has been assumed equal to 570 or 850 times the cost of the concrete (€/m^3), if the total volume of the device is higher or lower than 50 dm^3, respectively. The cost suggested by the Italian producers have been used.

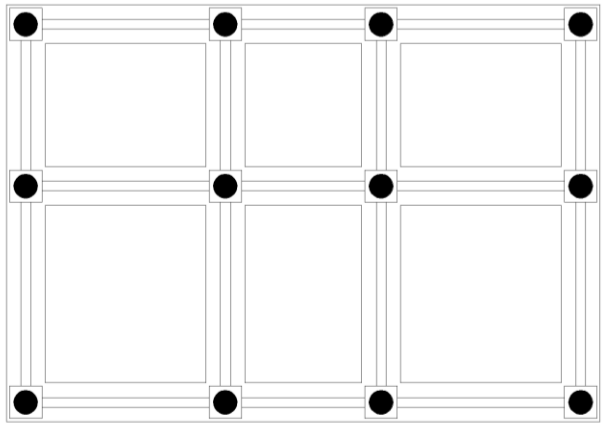


Figure 5.1. Deployment of the isolation devices

Table 5.2. Number and type of isolation devices (type HDRB indicates number-$D/t_i/n_g$; G = 0.8 MPa; type of SD indicates number-V/d_2)

Soil	*Iso.*	$a_g·S=0.25g$		$a_g·S=0.35g$		$a_g·S=0.45g$	
		B	*P*	*B*	*P*	*B*	*P*
Hard	*HDRB*	12-500/5/23	12- 500/5/33	12-500/5/29	10-500/5/34	12-500/5/17	12-500/5/20
	SD	-	-	-	2-1500/200	-	-
Medium	*HDRB*	8-550/5.5/26	8-550/5.5/34	12-550/5/19	12-500/6/19	12-550/5.5/17	10-550/5.5/28
	SD	4-3000/200	4-1500/200	-	-	-	2-1500/350
Soft	*HDRB*	6-500/5/32	-	12-600/6/16	6-500/5/29	8-650/6.5/36	8-600/6/36
	SD	6 -3000/200	-	-	6 -3000/350	4 -3000/400	4-1500/400

6. ECONOMIC COMPARISONS

The masonry thickness and the costs of the fixed base building for the three values of the spectral amplitude are compared with that of the isolated building (without the cost of the isolation system) in the cases of bricks (*B*) and poroton (*P*). The construction cost of the isolated building is always lower than the cost of the fixed base building. The difference becomes significant for high seismicity area.

The costs of the isolation systems have been finally added to those of the structure for each case. The results are summarized in Tab. 6.1 for the three seismic intensity areas and for both cases of brick (*B)* and *poroton* (*P)* masonry. It is worth noting that the cost of the foundation structure is influenced by the seismic acceleration S_e, but its influence is very low on the structural total cost.

Table 6.1. Comparison between the costs of the structures of the fixed base building and the seismic isolated building with underground level for brick (B) and poroton (P) masonry

Description		$a_g \cdot S=0.25g$		$a_g \cdot S=0.35g$		$a_g \cdot S=0.45g$	
case		*B*	*P*	*B*	*P*	*B*	*P*
Fixed Base		0.84	0.69	0.90	0.75	**1.00**	-
Base Isolated		0.84	0.68	0.84	0.68	0.84	0.68
Hard Soil	*Isolation system*	-	-	0.11	0.07	0.10	0.11
	Total BI	-	-	0.95	0.74	0.94	0.79
	BI/FB	-	-	1.05	0.97	0.94	-
Medium Soil	*Isolation system*	0.32	0.34	0.14	0.21	0.12	0.12
	Total BI	1.16	1.01	0.98	0.88	0.96	0.79
	BI/FB	1.38	1.53	1.08	1.17	0.96	-
Soft Soil	*Isolation system*	0.30	0.30	0.21	0.21	0.17	0.19
	Total BI	1.14	1.17	1.05	0.88	1.01	0.86
	BI/FB	1.36	1.75	1.16	1.17	1.01	-

7. CONCLUSIONS

Masonry buildings can certainly guarantee a durability longer than other construction materials and also a better performance in terms of energy efficiency, but masonry can still successfully used in the earthquake resistant structures, especially with seismic isolation. In this paper the application of base isolation in masonry buildings was analyzed. The study was referred to the case of very regular building, for which as already pointed out, it was not difficult and not expensive to realize a traditional structure without seismic isolation. The results showed that the use of base isolation is convenient, from an economic point of view, also with reference to the construction cost, in high seismicity areas, especially for hard soil. The convenience becomes much higher when referring the comparison to the life time of the building. In fact, seismic isolated building should not need reparation works, even after strong earthquakes.

As already said the numerical results are just relative to the case analyzed and cannot be generalized. Anyway, a complete comparison should account for other parameters. First of all the possibility to built higher masonry building when using seismic isolation, which results in lower cost for the same built volume. Besides, the economical suitability of seismic isolation for irregular buildings appears obvious both from the economical and architectural points of views. In fact, the cost of an irregular fixed base building increases significantly with the seismic intensity and is much higher than the cost of an equivalent regular building. Use of base isolation allows keeping low the cost of the superstructure, while the cost of the isolation system is not influenced significantly by the irregularity of the superstructure.

The analysis here reported could be improved by improving the modelling of the building, accounting for the inelastic behaviour of masonry and of the isolation devices. Obviously, isolation devices need to be substituted but their life time is comparable to that of the building.

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