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Base isolation for seismic retrofitting of flexible residential buildings

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ABSTRACT

Large cities facing post-seismic event trauma frequently make the choice of base isolation technology for the retrofitting or reconstruction of their strategic facilities to guarantee the continuity of the services critical to their population. Consequently, most hospital and other emergency buildings are base isolated in earthquake prone cities. On the contrary, the technology is very seldom used for residential buildings. In cities where a large part of the private housing building stock is made of 8 to 12-storey high RC frame buildings, two reasons are usually put forward to discard retrofitting by base isolation: the supposed high cost of the isolation system and its low efficiency due to the flexibility of the RC frame. Two recent case studies demonstrate the relevance of base isolation for the retrofitting of typical RC frame housing building. The design of the retrofitting of an 11-storey RC frame structure in Mexico City will first be presented. The second case study will detail the Moda Building in Istanbul, a 10-storey RC structure for which seismic retrofitting has recently been completed by Freyssinet using base isolation. The base isolation retrofitting of these two flexible buildings will be detailed in this paper, demonstrating the efficiency of such retrofitting solution for residential building, both in terms of cost and dynamic behaviour.

1 INTRODUCTION

Buildings are commonly classified according to their stiffness in 4 categories: stiff structures for vibration periods T < 0.3s, medium stiff structures for T ~ 0.3 to 0.7s, flexible structures for T ~ 0.7 to 1.5s and very flexible structures for T > 1.5 s. Base isolation is amongst the most advanced techniques for seismic protection of new and existing stiff and medium stiff structures; moreover, an effective design of the isolation system allows the structure to be fully operational even after major earthquakes. This is of fundamental importance for critical facilities such as infrastructures, hospitals, emergency operations and communications centres,. Seismic protection of stiff structures by base isolationhas been widely reported on the past years, and has been the subject of many technical publications

On the contrary, this technology is very seldom used for residential buildings which, in the geographical zones considered in this paper, are in majority made of reinforced concrete frames having a maximum height of 40m (8 to 12 storeys). With such residential buildings, seismic isolation is often discarded as a retrofit option for two main reasons: its supposed low efficiency due to the lateral flexibility of the RC frames and the high cost of implementing the isolation system. Although it is fully recognized that seismic isolation is more effective in the case of stiffer building (with vibration periods in the order of 0.2-0.7 sec), it is possible to demonstrate that even for flexible buildings (with periods in the order of 0.7 to 1.5s) seismic isolation can be the best option of retrofit in terms of cost, implementation time and structural resiliencein the case of strong seismic events. This article aims at illustrating the effectiveness of base isolation through two case studies: a typical building (11 storeys) in Mexico City and the Moda Building (10 storeys) in Istanbul.

2 FLEXIBLE RESIDENTIAL BUILDINGS

2.1 Typical flexible building in Mexico City

2.1.1 Characteristics and dynamic performances of the existing building

Following the Puebla earthquake that struck Mexico City in September 2017, a detailed design was carried out for the retrofitting of an administrative building (called *TFB* in the following) damaged during the earthquake. The building consists of an RC frame structure, which comprises an underground level used as parking space, a ground floor, a mezzanine floor, 7 standard floors, and a roof where the engine room of the elevator is located(Fig. 1). The building has a total of 11 levels for a height of 35.5 m and a constructed area of 387 m^2. The typical dimensions of the structure in plane is 13m x 31m.

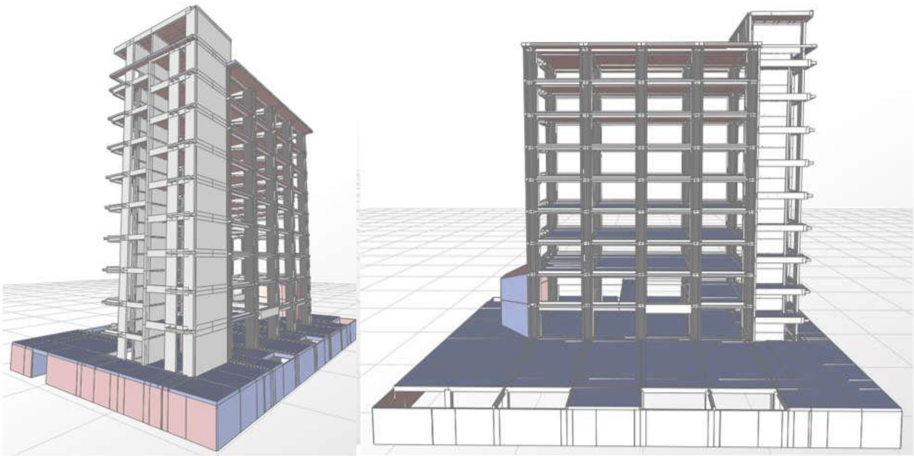

Figure 1: Isoviews of the TFB Building

The building was constructed in 1977. It is a flexible RC framed structure, with H-shaped columns and beams with a maximum length of 6 m. According to the visual inspections and physical tests performed, the frame resistant system is interrupted at the stairs and elevators, where columns and walls are made of low-strength concrete and have a low lateral stiffness. The floor system is based on light ribbed reinforce concrete slab 30 cm deep.

The building has suffered from several earthquakes since its construction. The visual inspection revealed an extensive damage of the beams, with widespread bending cracks at midspans and localized shear cracks at the supports. Even the columns, and in particular the central ones, are cracked at their upper ends at all floors of the building. The basement is made of a strong steel structure disconnected from the rest of the building and it therefore does not contribute to the lateral stiffness and resistance of the building, although it does provide bearing support in case of excessive vertical loads. At that level, corrosion was observed on the steel columns of the emergency stairway with substantial loss of plate thickness.

The stiffness of the building is irregularly distributed in plane, leading to an intrinsic torsional behaviour. This factor together with the low structural redundancy leads to important shear forces and deformations to the perimeter structural elements during possible seismic events. Figure 2 illustrates the first three modes of vibrations of the structure.

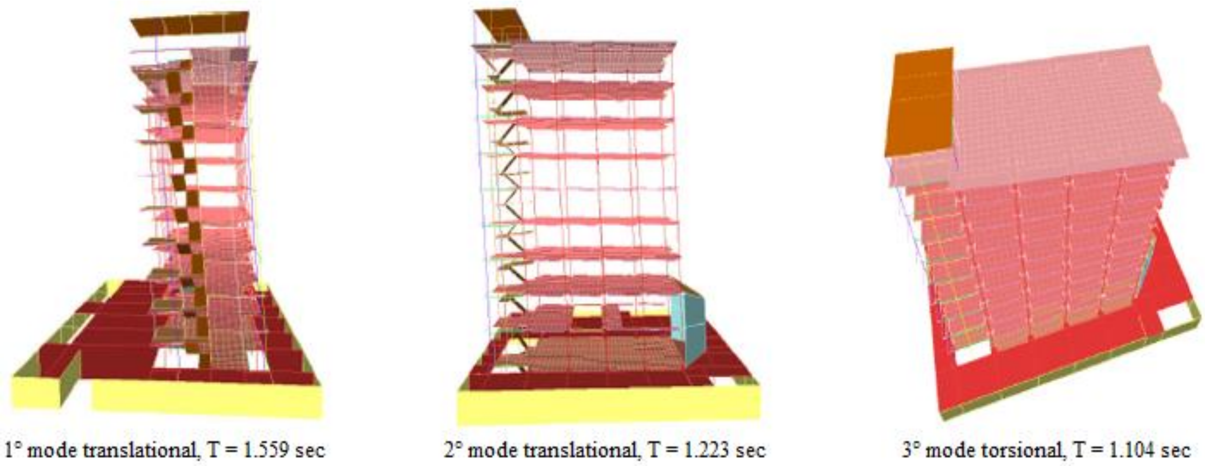

Figure 2: Vibration modes of the existing buildings

A linear dynamic analysis (response spectrum analysis) was performed to evaluate the seismic vulnerability of the building and highlighted the significant torsional issues. It was found that:

- the area around the stairs and the elevator is very vulnerable, with inter-storey drifts 43% higher than the rest of the structure, due to the lack of an efficient laterally resistant system.
- the deformation demands are excessive (76 cm in the short direction, 46 cm in the long one and about 50% of unsatisfied deformation checks according to the limits established by the National Building Code)
- had the building experienced the design earthquake, it would have partially or totally collapsed.
- the design base shear demand (17207 kN in the short direction and 23397 kN in the long one) exceeds the limited flexural and shear capacity of the structural elements, hence preventing the building from complying with the safety and stability conditions of any code and requiring to increase its lateral stiffness to prevent the high risk of partial collapse.

2.1.2 The retrofitting strategy

The TFB Building presents torsional problems, excessive lateral deformations, lack of capacity due to reduced flexural strength and low structural redundancy. Moreover, due to the widespread damage in the beams and the columns, and the incapacity of the walls to put up with shear forces and contribute to the global lateral stiffness, the building could not be reinforced by conventional methods. Therefore, it was decided to go for a base isolation system that would decrease the seismic energy transmitted to the structure and reduce the probability of damage at both service and ultimate limit states.

Lead Rubber Bearing isolators (LRB) from Freyssinet's ISOSISM® product range were used. These anti-seismic devices combine in a single unit the functions of vertical load support, horizontal flexibility and energy dissipation required for the base isolation of a structure. Figure 3 shows some features of this device.

Figure 3: LRB geometry (left), horizontal flexibility (centre) and hysteretic shear behaviour (right)

The anti-seismic devices are placed at the top of the basement (Fig. 4) together with flat sliding bearings to reduce the eccentricity between the center of mass and the center of stiffness of the building.

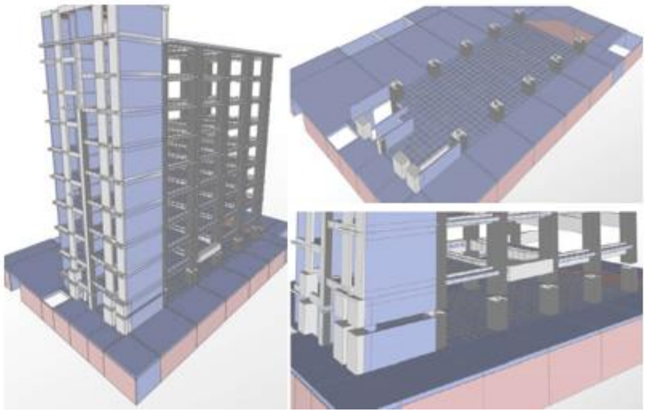

Figure 4: Views of the isolated building model

Figure 5 shows the modes of vibration of the isolated building.

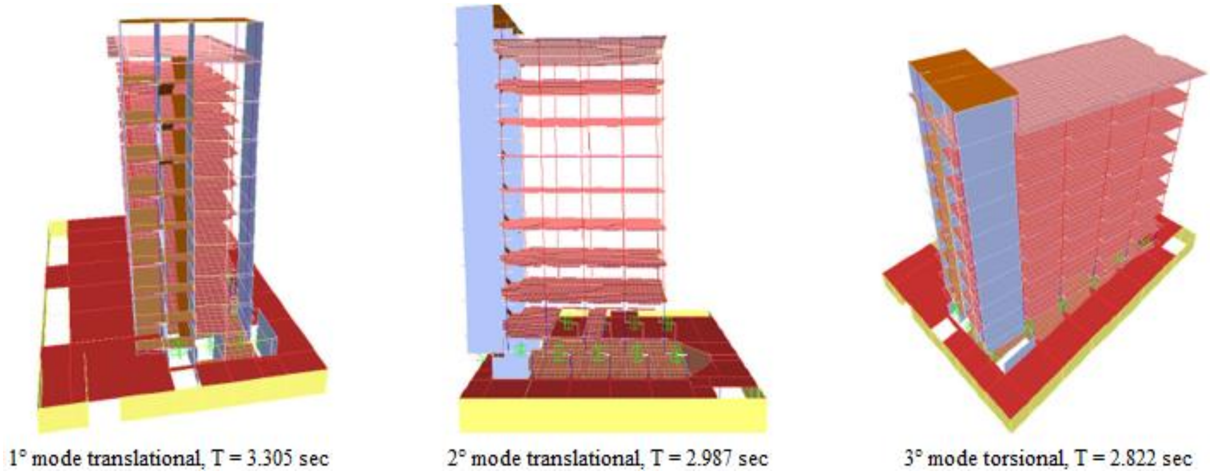

Figure 5: Vibration modes of the isolated building

The lengthening of the periods of vibration thanks to the lateral flexibility of the rubber coupled with the high damping capacity of the lead (30% for this project), reduces the pseudo-acceleration and hence the earthquake-induced forces in the structure by approximately 60% (6965 kN in the short direction and 8623 kN in the long one).

The drastic reduction of the seismic energy transmitted to the structure also has beneficial effects on the lateral deformation, which is now controlled and complies with the limits established by the National

Building Code, with a maximum deformation of 12 cm for the design earthquake at a height of 30 m. The beneficial effects of seismic isolation can also be clearly observed by comparing the design acceleration response spectra (Fig. 6), where the black dashed line represents the spectrum used at the time of building design, according to RCDF 1976 code.

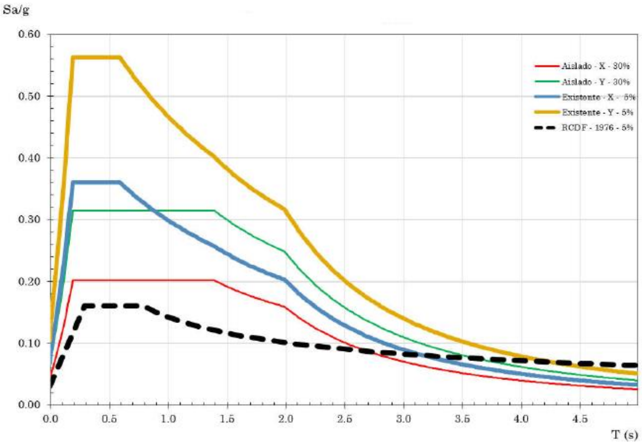

Figure 6: Comparison of design acceleration spectra before and after retrofitting

As the isolated structure undergoes lower seismic acceleration levels than in the pre-retrofitting condition, only the significantly damaged structural elements required to be locally strengthened. The retrofit included the wrapping of beams with carbon fibres to increase both their bending and shear capacities, the RC jacketing of some ground floor column sections and the strengthening of the mezzanine slab. A traditional retrofit solution without anti-seismic devices would have required a global reinforcement of the structural elements (all the beams and most of the columns), while not allowing the building to resist the design earthquake. The numerical results were validated through 7 non-linear dynamic analysis (time-history analysis), using synthetic spectrum-compatible accelerograms and modelling the complete hysteretic response of each LRB device (Fig. 7).

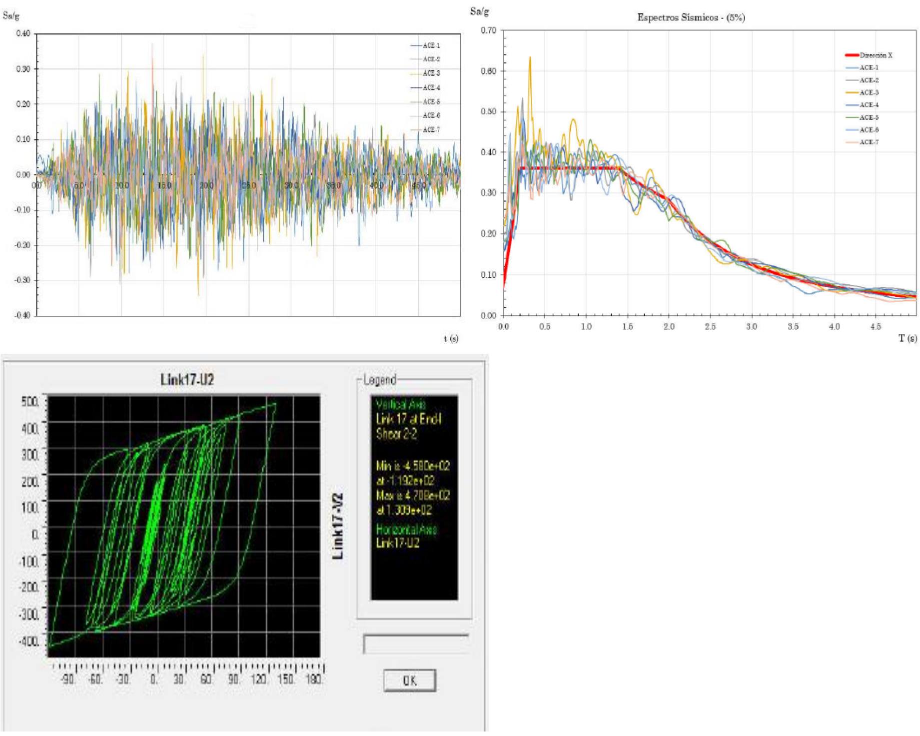

Figure 7: 7 synthetic records (top-left), spectrum-matching (top-right), LRB hysteretic response (bottom)

The solution with base isolation is in this case the most competitive strategy as it requires only 4-6 months to implement compared to 24 months to demolish and rebuild a new building with similar characteristic, and its costs are only about 32% that ofthe new building solution.

2.2 Moda Building, Istanbul

2.2.1 Characteristics and dynamic performances of the existing building

The Moda Building dates back to the 1980s and is located in the Kadiköy District of the Istanbul province. The building is a flexible structure having a height of 31m and a rectangular shape 14m x 22m in plane. It consists of 10 floors and an attic, with inter-storey heights between 2.60 m and 2.85 m and a total constructed area of 300 m^2 (Fig. 8). The building is a framed RC structure, with 24x50 and 60x95 cm columns and beams with varying cross-sections. The foundation system is constituted by individual plinths, with dimensions ranging from 110x110 cm to 250x250 cm.

Figure 8: Moda Building

Before assessing the seismic vulnerability of the existing building through non-linear static analysis (pushover analysis), an eigenvalue analysis was performed to better understand the dynamic properties of the structure. Figure 9 shows first 3 vibrational modes, highlighting the torsional deficiencies of the building.

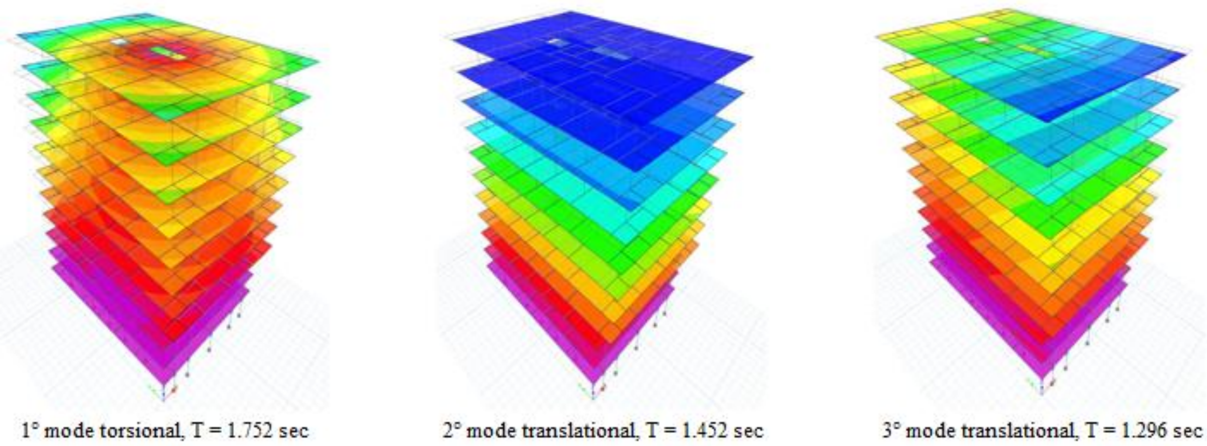

Figure 9: Vibration modes of the existing building

The pushover analysis confirmed the very limited lateral capacity of the building at the immediate occupancy limit state, with a maximum shear capacity of 2897 kN (7.2% of the total mass of the building) in the short direction and 2532 kN in the long one (6.3% of the total mass). With the acceptance of a reduction factor R =

2, the horizontal force/mass ratio that the structure could resist safely was only 12.6%. It was therefore decided to proceed with the retrofitting of the building.

2.2.2 The retrofitting strategy

As for the TFB example, the very limited seismic capacity of the building combined to a predominantly torsional behaviour led to opt for a base isolation strategy. It should also be noted that the traditional strengthening would have been necessary for most of the structural elements and therefore economically unviable. In this project, LRB isolators from Freyssinet's ISOSISM® product range were used. Flat sliding bearings were introduced to reduce the eccentricity between the center of stiffness and the center of mass of the building, so as to break down the torsional effects. The retrofit solution required the strengthening of the foundation slab to achieve the rigid diaphragm condition at the isolation level.

The seismic performances of the isolated building were assessed for the DBE (Design Basis Earthquake) and MCE (Maximum Considerable Earthquake) level through time-history analysis, using real spectrum-compatible accelerograms and modeling the hysteretic response of the devices. Figure 10 shows the numerical hysteretic response of a unit.

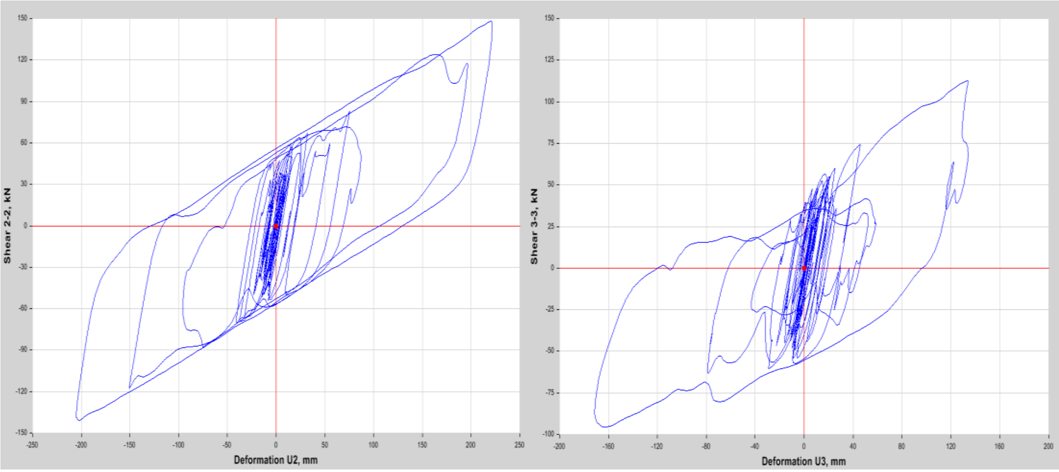

Figure 10: Force-displacement response of an LRB in the orthogonal horizontal directions

The base isolation solution proved effective as it allowed to satisfy all the strength and stability checks of the national code for a cost of approximately 20% of a new building.

The LRB devices were tested at ISOLAB (Italy), the innovative laboratory of the Freyssinet Group where both dynamic and static tests are performed as required by the main European and worldwide standards for Type Tests and Factory Production Control Tests. In this instance, testing according to the Turkish standards were performed for the first time on anti-seismic devices at the ISOLAB.

The installation of the isolators was performed by Freysas, a company of the Freyssinet Group based in Turkey. It consisted in the following steps:

1. Installation of two purpose built steel clamps tightened around the column through high strength steel prestressing bars.
2. Insertion of hydraulic jacks between the two clamps and pressurized until the column is fully unloaded.
3. Cutting a "slice" of the column using a diamond wire,
4. Installing the isolator after casting of the masonry plates.
5. Releasing the jacks to transfer the loads onto the bearings

It is important to note that this procedure does not interfere with the activities carried out at the higher levels of the building. Figure 11 illustrates two important steps of the procedure.

Figure 11: Cutting machine with diamond wire (left) and removal of portion of the column (right)

This solution allows to install the isolators quickly and easily, with flexibility in the construction sequence. The space requirements from both a structural and architectural point of view are also limited. Finally, the costs are comparable and often lower than traditional strengthening techniques.

3 CONCLUSIONS

The main objective of this article is to demonstrate the effectiveness of base isolation for RC flexible buildings, both in terms of cost and dynamic performances. Two case studies were presented in detail for this purpose: the 11-storeys TFB Buildingin Mexico City and the 10-storeys Moda Building in Istanbul. In both cases, the isolation retrofitting solution was developed and proved to be an efficient technical solution and the best economical option.

Through advanced non-linear dynamic analysis that accounts for the specific hysteretic behaviour of the isolators, it has been demonstrated that the buildings are able to support the seismic design action. In both cases, base isolation is the optimal choice of retrofit from a cost and programme point of view, compared to both traditional strengthening strategies and demolition/reconstruction of the buildings.

These projects, highlight the know-how of the Freyssinet Group in the seismic protection sector and its capacity to offer a turnkey solution: from the seismic assessment of the building to the design of the optimum isolation system; from the design, production and testing of anti-seismic devices to their installation using innovative and efficient retrofitting techniques.

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