Seismic Isolated Structures: Concept, Review, Design and Worldwide Application

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1. Introduction

This course presents a state-of-the-art on seismic isolation and the most important applications. After a brief introduction on the basic concepts of seismic isolation, applications to new strategic and public buildings are shown, as well as to new residential buildings, pointing out the very good behavior shown by the seismically isolated structures during real seismic events. Then, attention is focused on the retrofit of existing buildings, which represents the real challenge for the future. The most interesting applications on existing reinforced concrete, masonry and historic structures are shown, pointing out the specific challenges for each case.

2. Understanding Seismic Isolation Technique

It is well-known that seismic isolation increases the fundamental period of vibration of a building so that accelerations in the superstructure can be reduced significantly. This reduction is offset in terms of displacements, which increase substantially with the vibration period (Fig. 1, dashed line). However, in the presence of isolation devices, these displacements can be concentrated at the base of the building, while the superstructure behaves almost like a rigid body. Seismic actions on structures can be described by the acceleration elastic response spectrum at the site, which assumes the shape shown in Fig. 1 (continuous line), according to both Italian and European codes. In the range [TB, TC] the acceleration is constant, and is equal to its maximum value:

$$S_{e,\,\max} = a_g F S \eta$$

where a_g is the peak ground acceleration on rigid ground, F is the structural amplification factor, S is the soil amplification factor and $\eta = \sqrt{10/(5+\xi)}$ is a damping coefficient that corrects the elastic spectrum for values of the damping ratios ξ different from 5% (η = 1 for ξ = 5%, which represents the reference value for conventional structures). In the range [TC, TD], characterized by a constant velocity, the elastic spectrum is:

$$S_e(T) = S_{e,\,\max} \frac{T_C}{T}$$

For T > TD, it is characterized by constant displacement:

$$S_e(T) = S_{e,\,\max} \frac{T_C T_D}{T^2}$$

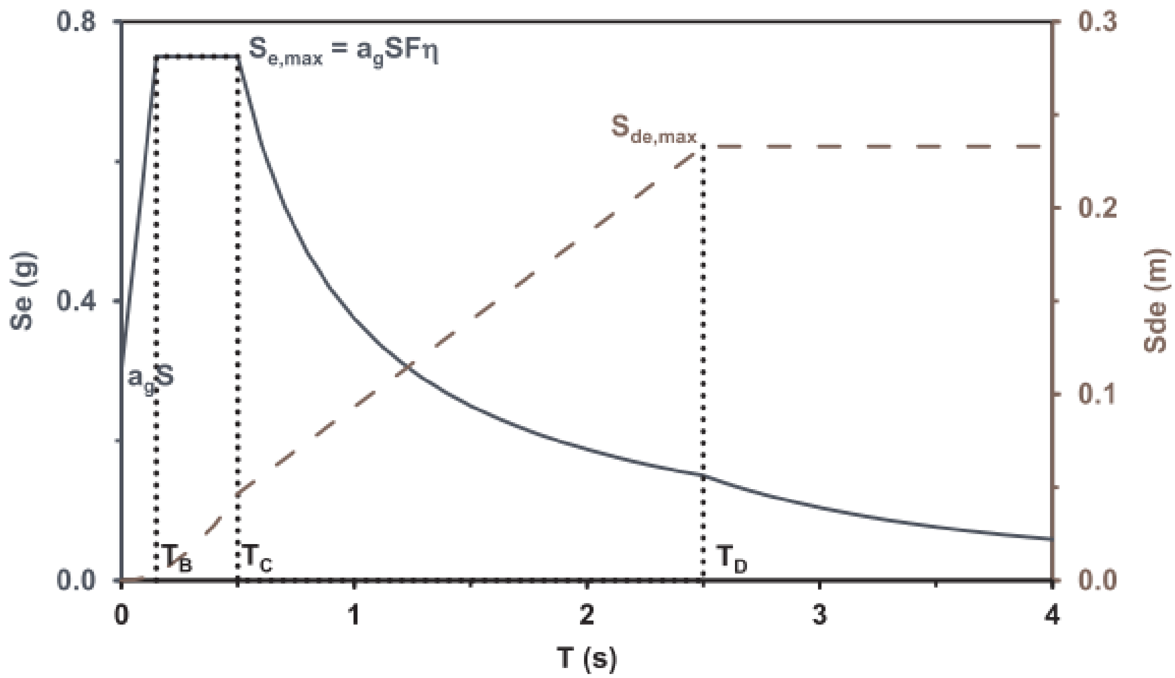

Figure 1: Elastic response spectrum

The usual values of the fundamental periods of vibration of conventional structures are often in the range of maximum seismic amplification.
The actual reduction of the seismic action due to the use of seismic isolation is given by the spectral ratio

$$\frac{S_{e,is}}{S_{e,fb}} \cdot \frac{\eta_{fb}}{\eta_{is}}$$

where $S_{e,is}$ is the elastic spectral amplitude at the fundamental period of vibration of the isolated building T_{is}, and $S_{e,fb}$ is the elastic spectral amplitude at the fundamental period of vibration T_{fb} of the same building considered as fixed at its base. This ratio also accounts for the higher damping introduced by the isolation devices with respect to the conventional building. Usually η_{fb} = 1 and $\eta_{is}/\eta_{fb} < 1$. In Fig. 2, this spectral ratio is plotted versus T_{is}/T_{fb}. The two cases of $T_{is} \in]T_C, T_D]$ and $Tis \in]T_D, 4.0]$ must be distinguished. In the first one, the curve (upper line) is unique if $T_{bf} = T_C$ is assumed when $T_{bf} \leq TC$. In the second case, different curves for different values of T_{bf}/T_D (T_D = 2.5 s was assumed) are plotted. These start from the upper curve at the abscissa at which $T_{is} = T_D$. As one can see, acceleration reduction reaches substantial values, especially for $T_{is}/T_{fb} \geq 3$, which is also a suitable value to guarantee the decoupling of motions between the structure and the soil.

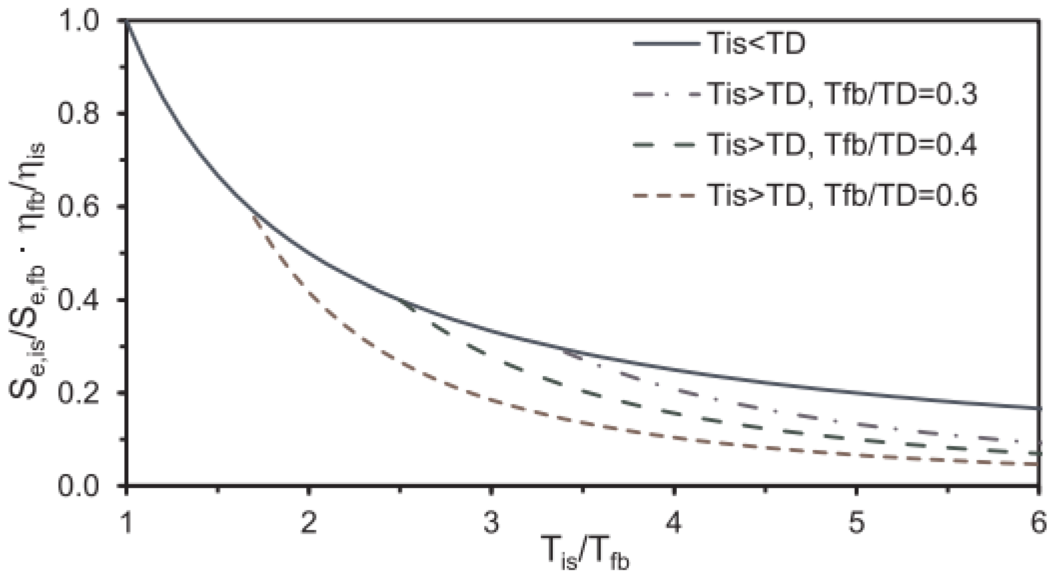

Figure 2. Elastic spectra ratios Se,is/Se,bf.

The first modern application of seismic isolation in Italy dates 1976 and concerns the Somplago Viaduct of the Udine-Tarvisio freeway (Fig. 3). Thanks to its seismic isolation system (comprising sliding devices on the piers and rubber bumpers between the deck and the abutments), the Somplago viaduct survived the two shocks of the September 11th (magnitude M = 5.3 and 5.6, respectively) and the two shocks of the September 15th (M = 5.9 and 6.0, respectively), 1976 Friuli earthquake, with epicenters only a few kilometers from the viaduct. This was without any damage, contrary to most other structures located in the epicentral area.

Figure 3. The seismically isolated Sompago viaduct of the Udine-Tarvisio freeway, after its completion, Italy.

The excellent behavior of the Somplago Viaduct, dating from the years of construction of the Italian highway system, caused an immediate rapid extension of the application of anti-seismic systems to new Italian bridges and viaducts. The devices used were mainly dampers and Shock Transmitter Units (STUs). The bridges and viaducts protected by such systems numbered already 150 at the beginning of the 1990's: this ensured, at that time, worldwide leadership to Italy for the number and importance of anti-seismic systems applied to bridges and viaducts.

The first Italian application of seismic isolation in buildings dates 1981 and concerned a fire-command building in Naples (Fig. 4). It is a steel structure suspended from a top reticular beam, which is supported by reinforced concrete towers. The building had been designed before the November 23rd, 1980, Campano-Lucano earthquake (M = 6.9), without accounting for seismic actions, the area not being considered seismic at the time. As a result, the original design was retrofitted by just inserting Neoprene Bearings (NBs) at the top of the reinforced concrete towers as supports for the reticular steel beam, and floor dampers and Shock Transmitter Units inside the building (structural design by F.M. Mazzolani). Similar devices were used also for a second fire-command building nearby, which was opened for use in 1985.

Figure 4. The first seismically isolated fire-command building in Naples, Italy

The progress of applications of new anti-seismic technologies (including energy dissipation systems) in buildings was slower in the following years; however, the trend accelerated in the beginning of the 1990s, following the construction of the Telecom Italia Centre of the Marche Region at Ancona. In total, 297 High Damping Rubber Bearings (HDRBs) were used and impressive on-site release tests were performed on one of the five buildings (Fig. 5, structural design by G. Giuliani, acceptance certificate by A. Martelli).

Figure 5. The Telecom Italia Centre in Ancona, completed in 1992

Nowadays Italy is the fifth country in the world and the first country in Western Europe for the overall number of applications of passive anti-seismic devices. As far as seismic isolation is concerned, it is the fourth country in the world for the number of isolated buildings, with over 400 applications already in place by 2013. In several applications, the isolators used are HDRBs and plane surface Sliding Devices (SDs), often used in parallel to optimize the dynamic behavior of the structure. More specifically, the stiffness center of the isolation system should be almost coincident with the projection of the center of gravity, to minimize torsion effects. Lead Rubber Bearings (LRBs), which enable a higher damping (up to an equivalent damping ratio of 25–28%), are used especially for bridges and viaducts. Finally, single and double Curved Surface Sliders (CSSs) were introduced in Italy after the 2009 L′Aquila earthquake (M = 6.3) and are now widely used in buildings. In this course a state-of-the-art on seismic isolation in buildings in Italy is presented. The evolution of the seismic code is first traced, and then an overview of the most interesting applications follows. The importance of structural monitoring to improve knowledge under different loading conditions is finally emphasized.

3. The Importance of Design Codes in the Seismic Isolation of Structures

As already mentioned, Italy was among the first countries in the world to apply seismic isolation, especially to bridges and viaducts. In spite of this, a suitable design code was missing until 2003. This was the main reason for which the use of seismic isolation was very limited before that year. Due to the absence of specific rules for structures with seismic isolation in the Italian Technical Code, all designs of such structures had to be submitted for approval to a special committee of the Ministry of Infrastructures. The first technical reference in Italy containing the design rules for seismic isolation, the so called “Guidelines for the design, execution and testing of seismic isolated structures”, was issued in 1998. The guidelines did not constitute an effective code, so the approval process was not abolished and continued on, being uncertain, very complicated and time consuming. Obviously, this did not encourage the application of seismic isolation in Italy. After the October 31st, 2002 Molise earthquake (M = 5.4), when the collapse of the Francesco Jovine School building in San Giuliano diPuglia, which was very close to the epicenter, caused the death of 27 children and their teacher, shocking the public opinion, the Italian seismic code was revised under the Ordinance 3274/2003 issued by the Prime Minister's Office in March 2003. The new Italian seismic code included innovative aspects with respect to the previous codes, among these:

- the limit states method was the only check method allowed for structures also in seismic areas, while the allowable stresses method was abolished;
- suitable design rules were given for seismic isolation and energy dissipation systems, the use of which was allowed without any additional approval.

After a period of confusion, in which different technical codes coexisted, in 2008 the new Italian Technical Code was finally issued. It includes all the revised technical codes, which had been issued separately in the past, and became the only valid technical code in July 2009, after the L′Aquila earthquake.

Obviously, the presence of a suitable code encouraged the use of seismic isolation, especially for strategic structures, such as those for civil protection purposes, and public buildings, such as schools and hospitals. For these structures, in fact, higher levels of safety are required, which could be hardly obtained with traditional techniques. For ordinary building, on the contrary, the safety requirements are lower and any increase of the construction cost, due to base isolation, does not encourage its use. Actually, the Italian code allows designing the superstructure with the effective seismic action, which is much lower than that one should consider for a fixed base building. So, the cost of base isolation can be balanced by savings in the superstructure. The economic suitability of seismic isolation depends on several factors, among which are the earthquake intensity and the soil characteristics, but also the shape and the size of the building. A wide numerical analysis was carried out by Clemente & Buffarini with reference to reinforced concrete buildings. They concluded that:

- The difference between the cost of a building designed with a fixed base and the same building designed with base isolation is in general very low; furthermore, if well designed, a base isolated building costs less than a fixed base one.

- Differences are certainly negligible for buildings in high seismicity areas (i.e., where ag ≥ 0.20 g on rigid ground with probability of exceedance ≤ 10% in 50 years), where the solution with base isolation could be even less expensive. For medium and low seismicity areas, the use of base isolation could also be convenient, especially for irregular and special buildings.

- One should account for the larger useful area due to the smaller size of columns in the solution with base isolation, which translates in higher value for the building.

A parallel analysis was performed also for masonry buildings, obtaining quite similar results. The use of seismic isolation is certainly suitable if one refers the comparison to the life span of the building. In fact, correctly erected seismically isolated buildings will not need reparation work, even after an earthquake of the same intensity as the design one. Furthermore, it must be noted that a higher level of safety is required for the devices. This is usually obtained, according to the Eurocode, by amplifying the seismic design displacement, obtained for the seismic action concerning the ultimate limit state by a reliability factor. On the contrary, two different ultimate limit states are defined in the Italian Technical Code, the so-called Life Safeguarding Limit State (SLV) and the Collapse Limit State (SLC). The first concerns the superstructure and considers a seismic action with a probability of exceedance of 10% during the reference time period (which coincides with the life span for ordinary buildings and is 1.5 or 2.0 times higher for relevant and strategic buildings, respectively), while the second considers a seismic action with a probability of exceedance of 5% during the reference time period and is used for the isolation devices. This gives a more correct evaluation of the different safety factors, especially when following a probabilistic approach. One can conclude that a suitable comparison between traditional and base isolated buildings should be made by referring to the same structural target in terms of the degree of safety. In other words, one should design the fixed base building in the elastic range. In this case the superiority of seismic isolation in terms of construction cost becomes very high.

4. Overview of the Application of Seismic Isolation

Initially, seismic isolation was developed for reinforced concrete buildings. For this structural type, it seems suitable to place one device for each column at the underground level, in order to transmit the vertical loads directly to the foundations. Otherwise, a structure with a suitable bending stiffness should be designed to transfer the actions from the columns to the devices. Furthermore, a horizontal rigid diaphragm is necessary between the superstructure and the isolation system, and a minimum height is required for the isolation interface floor in order to allow inspection of the isolators and for their replacement. Thus, it is certainly useful to make the isolation interface floor high enough and to use it as a parking lot or something similar. From a structural point of view, the devices could be placed at any intermediate height or even at the base of the columns, the only requirement being that the structural elements between them and the supporting deck should be rigid enough in comparison with the devices themselves. It is important to observe that in the case of isolators at the base of the columns, these will not shake in tandem with the lower floor in case of an earthquake; consequently, a gap should be designed to absorb the relative displacements. For these reasons the solution with devices at the top of the underground level has to be preferred.

With reference to their locations in plain view, the isolation devices should be deployed so as to optimize the dynamic behavior of the building, i.e., to obtain the first two modal shapes as translational ones with no torsion. This is almost automatic when using Curved Surface Sliders (CSSs), for which the lateral stiffness of each device is related to the vertical load on it; as a result, the stiffness is distributed according to the masses and a shift in the center of gravity results in an equal shift in the center of stiffness, limiting eccentricity. Therefore, the period of vibration is determined mainly by the curvature radius. In the case of High Damping Rubber Bearings (HDRBs) and Sliding Devices (SDs), these should be placed with the aim of obtaining the stiffness center almost coincident with the projection of the superstructure gravity center, and then the period of vibration depends on the total stiffness of the isolation system.

In the following, an overview of the most interesting cases of seismically isolated reinforced concrete buildings in Italy is shown. It should be clear that these applications followed major earthquakes that occurred during the last decade.

4.1 Applications after the 2009 L′Aquila Earthquake in Italy

The use of seismic isolation increased rapidly after the L′Aquila earthquake of April 6th, 2009, starting from buildings for temporarily hosting the homeless residents (C.A.S.E. project). These consisted in pre-fabricated houses, made of reinforced concrete, steel or wood, each placed on an isolated reinforced concrete slab (21 m x 57 m in plan, 50 cm thick) supported by 40 CSSs manufactured in Italy, installed at the top of the columns, rising up from the foundation plate, which had the same size as the slab (Fig. 6).

Figure 6. One of the buildings of the C.A.S.E. project, isolated by means of Italian CSSs in 2009

Afterwards, seismic isolation was largely used in the reconstruction in L′Aquila and the surrounding towns, both for new and existing buildings. Thus, the number of Italian seismically isolated buildings increased from about 70 before L′Aquila earthquake to more than 400 by 2013 (with over 30 applications to school buildings). A further incentive to the use of seismic isolation for reconstructions was the 2012 Emilia earthquake.

One of the first building completed during the reconstruction in L′Aquila was the ANAS (Italian National Agency for Roads Construction) building, isolated by means of 60 HDRBs and completed in 2011 (Fig. 7).

Figure 7. The ANAS building in L'Aquila

Among the most interesting applications, outside the areas hit by recent earthquakes, are:

- a commercial building in Augusta, which has a rectangular shape with a length of 35.70 m, a width of 16.00 m, a maximum height above the ground of 10.50 m and a basement story with a clear height of 3.60 m (Fig. 8); the hybrid seismic isolation system consisted of 16 HDRBs and 20 SDs. The building was subjected to a series of push and sudden release tests in March 2013, with low amplitudes to ensure that no damage would occur in the finished structure. During the tests, the displacements at the isolation level were measured along with the accelerations at each floor of the building.

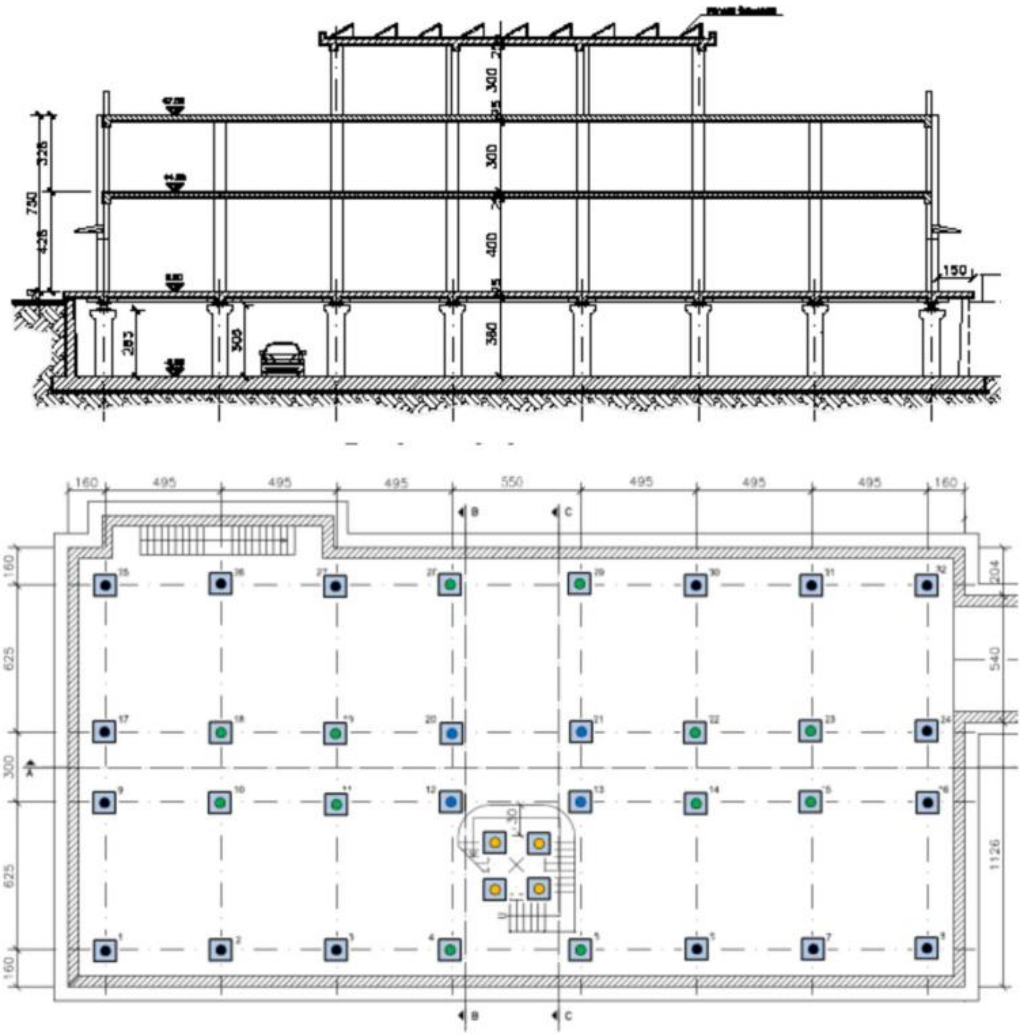

Figure 8. The commercial building in Augusta

- a residential building in Spadafora Street at Messina, the tallest seismically isolated building in Italy, completed in 2014 (Fig. 9, structural design by M. Marino, acceptance certificate by A. Martelli), composed of 8 floors plus an underground floor, used as garage. It was isolated by means of 22 LRBs and 2 SDs. The vicinity of an old building to the new isolated one pointed out the issue of protection of the seismic joints from materials coming from the adjacent structures in case of their collapse during an earthquake.

Figure 9. The residential building in Spatafora Street in Messina, which is the tallest seismic isolated building in Italy.

- The “120 Forlanini” residential building in Ragusa completed in 2014 (Fig. 10, structural design by C. Mezzasalma), with a reinforced concrete structure and an isolation system composed by 17 HDRBs (diameter = 450 mm, total rubber thickness = 126 mm) and 18 SDs, which ensured a fundamental period of the five floors superstructure equal to 3.0 s and a maximum displacement of 250 mm.

Figure 10. The “120 Forlanini” residential building in Ragusa (Courtesy of FIP Industriale)

- The “Balza Akradina” residential building in Siracusa completed in 2015 (Fig. 11, structural design by N. Impollonia), with a reinforced concrete structure and an isolation system composed of 8 HDRBs (diameter = 500 mm, total rubber thickness = 102 mm) and 4 SDs. The fundamental period of the five floors superstructure is 2.4 s and the maximum displacement is 200 mm.

Figure 11. The “Balza Akradina” residential building in Siracusa (Courtesy of FIP Industriale, N. Impollonia and Assennato Costruzioni)

- The Eurosky building in Rome (Fig. 12), where 30 SDs and 28 LRBs (diameter = 800 mm, horizontal stiffness = 5800 kN/m, equivalent damping = 25%) were used to obtain a tuned mass damper (TMD) at the twenty-seventh floor, using the upper three floors as mass; pretensioned vertical bars were also used to avoid rocking effects.

Figure 12. The Eurosky building in Rome

5. Seismic isolation in Masonry buildings

Masonry walls transfer loads to the foundations along their entire base length, while the isolators concentrate the loads only in certain locations. It is clear that the choice of these locations is a fundamental issue. A suitable solution is to build a very rigid structure under the masonry walls at the first level, which should be able to absorb all local actions from the superstructure and transfer them to a limited number of devices. These should be placed mainly at the wall crossings and, if the distances are too long, additional isolators should be inserted between them. With reference to the height of the isolation device locations, the same considerations made for concrete buildings are still valid (Fig. 13).

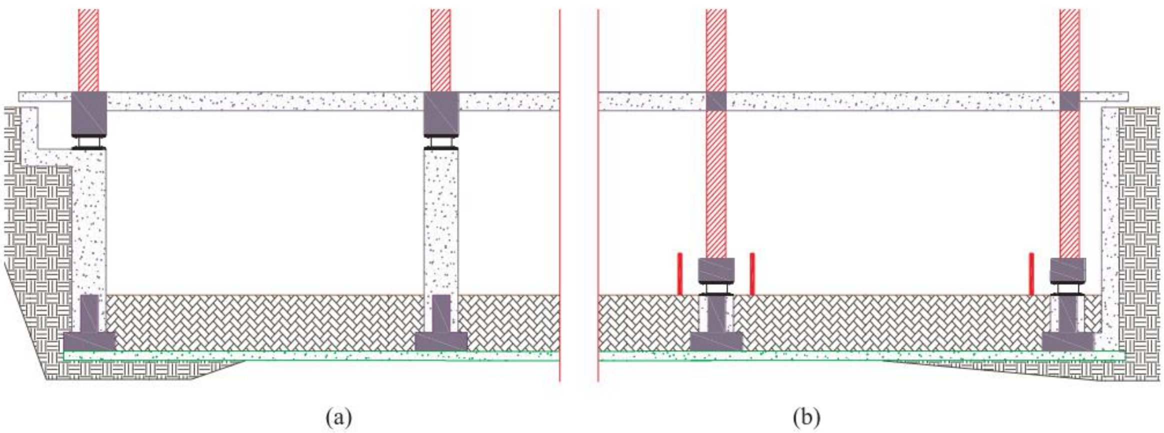

Figure 13. Isolation system (a) at the top and (b) at the base of the underground level.

One of the first applications of seismic isolation to masonry buildings in Italy was the residential building in Corciano, composed of two blocks of two and four floors, respectively (structural design by A. Parducci). The isolation system is made of 18 HDRBs (diameter = 500 mm), placed between the reinforced concrete foundation and the superstructure. The superstructure is reinforced masonry, with hollow bricks, because at the time of construction the Italian code did not allow normal masonry buildings of four levels or more in high intensity seismic areas.

The interest for use of masonry in new buildings is related to the fact that masonry can guarantee a longer durability, testified by ancient constructions, and a better performance in terms of energy efficiency. It is clear that seismic isolation can contribute to the revival of masonry in structures, reducing greatly the seismic effects to the structure. To assess the potential of brick masonry buildings, ENEA and ANDIL (the Italian association of brick manufacturers) organized a research project, which led to the design of a brick masonry building with seismic base isolation, to be used as a strategic structure. Seismic isolation allowed more freedom in the architectural design with obvious good results in terms of functionality and use of space. In addition, the building is a net-zero energy building (NEZB) and has an eco-friendly connotation, thanks to the use of brick materials and low environmental impact systems.

6. Retrofit of Existing Buildings

The real challenge of seismic isolation is protection of existing structures, especially in countries such Italy where maintenance of old structures is an important issue. It is worth reminding that base isolation yields a very high level of safety and that the period of vibration can be chosen so as to allow input of low spectral amplitude, while the superstructure remains in the elastic range. This possibility also allows for limiting or even avoiding the conventional retrofit intervention in the superstructure. While the positioning of the isolation devices in plan in existing buildings follows the same rules already discussed for new buildings, the positioning in elevation is influenced by the existing foundation layout and the presence of architectural and structural constraints, such as stairs and elevators, and their geometry. Furthermore, a fundamental issue is the temporary transfer of loads during the various operations until the final loading of the isolators, usually pursued by means of flat jacks injected with epoxy resin. In the following, some applications are shown.

6.1 Retrofit of Reinforced Concrete Buildings

With reference to reinforced concrete buildings, there are mainly two types of interventions for placing the seismic isolation system:

- To cut and eliminate a portion of the columns (and the walls, if any), and successively to insert the isolators. As is the case for new buildings, the best solution, when possible, is to insert the devices at the top of the columns of the lowest floor (the underground floor, if any). In this way, the floor above the isolators guarantees the horizontal stiffness level required and the portions of the columns under the isolation devices can be enlarged to obtain the stiffness needed or just to support the isolators.

- To insert the devices between the existing foundations and new sub-foundations, which must be custom built. Sometimes, the existing foundation is not structurally reliable, and two new foundations should be built.

The second technique was applied, for the first time in Western Europe, to a residential building in Latini Street at Fabriano (Fig. 14, structural design by G. Mancinelli, acceptance certificate by A. Martelli), which suffered damage to non-structural elements during the 1997-98 Marche-Umbria seismic sequence. New plinths were built under the existing ones (each of them was supported by two piles) and the seismic isolation devices were inserted between the new and the existing plinths. The isolators were loaded using flat jacks injected with epoxy resin and finally the existing piles were cut, thus separating the old and the new plinths. This building, which is located in the area affected by the 2016–2017 seismic sequence in Central Italy, did not suffer any damage at all, contrary to other conventional buildings in the same area, which were also reconstructed after the 1997-98 Umbria and Marche seismic sequence.

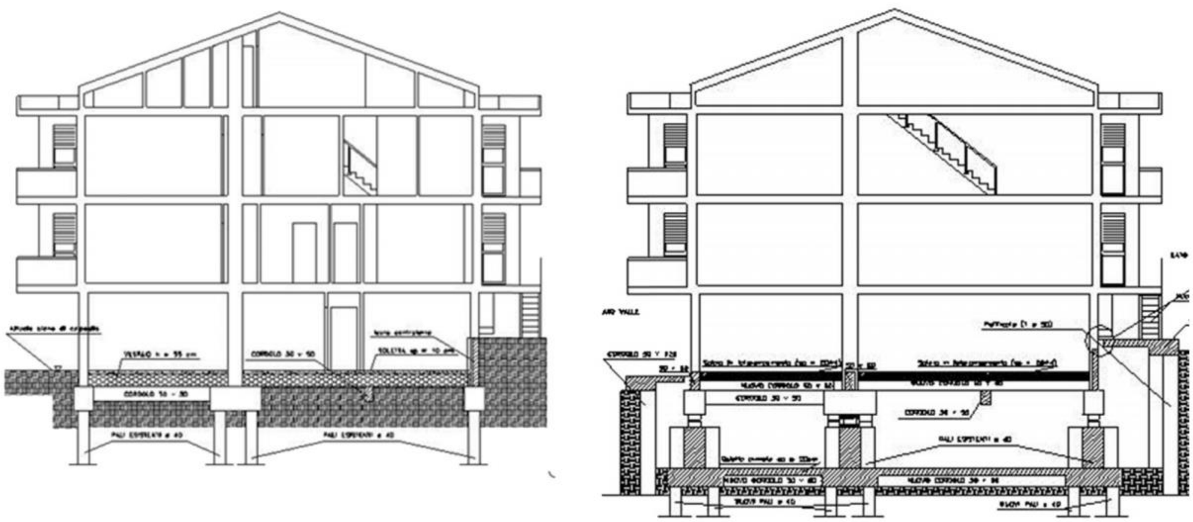

Figure 14. Vertical section of the reinforced concrete building in Latini Street in Fabriano, Italy before and after the insertion of base isolation

The second technique is more suitable and was used in several cases. Among the first applications, we mention the Multifunctional Centre at Rione Traiano in Naples, which has an asymmetric shape. It had been built before the 1980 Campano-Lucano earthquake, when the area was not classified as seismic, but remained incomplete. The building was retrofitted in accordance with the new Italian seismic classification and technical code and completed in 2005, by inserting 630 HDRBs in the columns and in the outer walls, above the foundation level. A steel frame above the isolation interface was also inserted (Fig. 15); the intervention cost was of about 80 €/m^2.

Figure 15. The cut of one column of the Poly-functional Centre Rione Traiano in Naples

The same technique was used also for the retrofit of two, four-story reinforced concrete residential buildings in Solarino, Sicily (structural design by G. Oliveto and M. Granata). Seismic action was not considered in the original design. Then, the building site was abandoned after the concrete skeleton and the perimeter and partition infilling walls had been completed. The short columns of the underground floor were used to insert the isolation devices. The new period of vibration is 2.35 s, and the maximum displacement is 141 mm. The intervention was completed in 2003 and the structure was subject to a release test with initial displacement similar to the design one.

Seismic isolation has been largely used after L′Aquila earthquake also for retrofits. One of the most interesting interventions was that of the "Leonardo complex” in L′Aquila (Fig. 16).

Figure 16. Leonardo building. Insertion of an isolation device (courtesy of FIP Industriale).

The structure consists of three structurally independent buildings, resulting in an approximately "L-shaped" building, each with four stories above the ground and a basement. The two main lateral buildings are connected to the central building housing the elevator shaft. The supporting structure is made of reinforced concrete frames, with reinforced concrete and hollow tiles mixed floors. The foundations are made of concrete beams (70 cm × 70 cm). During the 2009 L′Aquila earthquake the structure exhibited widespread damage to the masonry infill walls, especially at the ground floor, with cracking at the joints due to hammering and limited capillary cracks at the joints of the reinforced concrete frame. A vulnerability analysis was first carried out, and then a retrofit intervention scheme based on the insertion of double concave, curved surface sliding isolators at the top of the basement columns was chosen. This technique limited the intervention to the lower floors, where large-scale repairs to the damaged infill walls were necessary anyway. The fundamental period of the structure was brought up to 2.75 s.

The installation of the isolators required the following steps for each column:

- Enlargement of the column at the basement and simultaneous preparation of ferrules to be used for the anchoring of the lower lifting steel brackets. Also, recesses to be used for the lower anchorage of the isolator with dowels.
- Core drilling of the upper part of the column and provision of the ferrules for the anchorage of the upper lifting brackets.
- Installation of metal brackets and placement of hydraulic jacks to unload the part of the column to be removed.
- Diamond wire cutting, removal of the segment of the column, and levelling of the lower surface.
- Insertion of the metal brackets for the anchorage of the upper part of the isolator.
- Insertion and screwing of the isolator and subsequent grouting of the anchors and the collar with anti-shrinkage cement mortar.
- Removal of jacks and loading of the isolator.

Among the other relevant applications worth mentioning are:
The residential building in Tigli Street at Pianola, L′Aquila (Fig. 17), which had been severely damaged by the 2009 L′Aquila earthquake. The structure was composed of three blocks, which were first studied by means of experimental vibration analysis, in order to identify their dynamic characteristics. Then, the three blocks were joined at the first floor and 42 HDRBs and 62 SDs were inserted at the top of the columns just below the first floor and below the stairs (structural design by G. Mancinelli, acceptance certificate by A. Martelli). An inspection carried out after the Central Italy earthquake of August 24th, 2016, (Mw = 6.0) showed that the building behaved very well;

Figure 17. The reinforced concrete buildings in Pianola, L'Aquila (courtesy of FIP Industriale)

- The Quasimodo School at Riposto, Catania, which was seismically isolated in 2009 by means of 33 HDRBs and 16 SDs. It was the first Italian application of seismic isolation in existing schools, with a retrofit cost of only 45 €/m3 (structural design by F. Neri, Fig. 18);

Figure 18. The school of Riposto, Catania

- The IACP building at Calatabiano, Catania, built at the beginning of 1980s with a rectangular shape in plan (size 35.5 m × 11.25 m), three floors above the ground plus an underground floor. The carrying structure was composed of reinforced concrete frames and brick-concrete floors, and the foundation was a plate stiffened by a grid of beams. The structural elements were in very bad conditions, due to the carbonation of concrete and the steel corrosion. The retrofit was done by means of seismic isolators at the top of the columns at the underground floor (structural design by F. Neri). The columns of the underground floor were first enlarged, both to improve their strength and to allow the insertion of the devices, and additional beams were built just above the isolators. Next, thirty-three CSSs were used, the fundamental period is now 2.71 s, the maximum design displacement is 220 mm.

6.2 Retrofit of Masonry and Cultural Heritage Buildings

Seismic isolation has been largely used after the L′Aquila earthquake for the retrofit of masonry buildings. The most interesting applications concern historic buildings, e.g.:

- The Palazzo Ciuffini-Cricchi-Volpi, a masonry building located in the historical center of L′Aquila, which was badly damaged by the 2009 earthquake, and then retrofitted with seismic isolation (structural design by R. Vetturini); specifically, 28 HDRBs (diameter =550 mm, total rubber thickness = 105 mm) and 25 SDs were used. The choice of the isolation period was governed by the displacement, which had to be limited because of the presence of an adjacent building (Fig. 19). The isolated period was 2.02 s and the maximum displacement 146 mm. The isolators were placed between two new sub-foundations made of reinforced concrete beams;

Figure 19. Aerial view of Palazzo Ciuffini-Cricchi-Volpi in L'Aquila and an HDRB

- The historical masonry building called "La Silvestrella" in L′Aquila, which was also seriously damaged by the 2009 L′Aquila earthquake. The structure had been built in the early years of the twentieth century and was kept in its original configuration, without changes or superfetation. Therefore, it represents an uncommon example of eclectic, fantastic, grotesque architecture. A traditional strengthening intervention, which respected its historical value and guaranteed a suitable safety level, was not possible in practice, so it was decided to use seismic isolation (structural design by R. Vetturini). The executive phases were the following. The superstructure was first consolidated and protected. Then, two sub-foundations were built, one above the other and the devices were places in between (Fig. 20). The upper one consisted in continuous concrete beams, while the lower one was composed by plinths, which were successively connected by means of a reinforced concrete plate. The isolators were first connected to the upper sub-foundation, where suitable steel elements had been previously positioned. Then jacks were positioned under them, which allowed loading the isolators, by means of injection of epoxy resin. A steel floor above the isolation interface guaranteed the rigid connection, but also formed a new floor. Finally, 25 HDRBs (diameter = 450 mm, total rubber thickness = 126 mm, damping ratio = 13%) and 23 SDs were used, yielding a fundamental period of 2.35 s and a maximum displacement of 300 mm;

Figure 20. View of the historical masonry building called "La Silvestrella", L'Aquila, and a HDRB

- The so-called "Emiciclo building" in L′Aquila, which is the main branch of the Abruzzo Region Council (Fig. 21, structural design by R. Vetturini, G. Di Marco, L. Zazzara, W. Cecchini and A. Bottone, consultancy by A. Borri); the building was seismically isolated by means of 61 HDRBs and 47 SDs, which allow a maximum displacement if 300 mm.

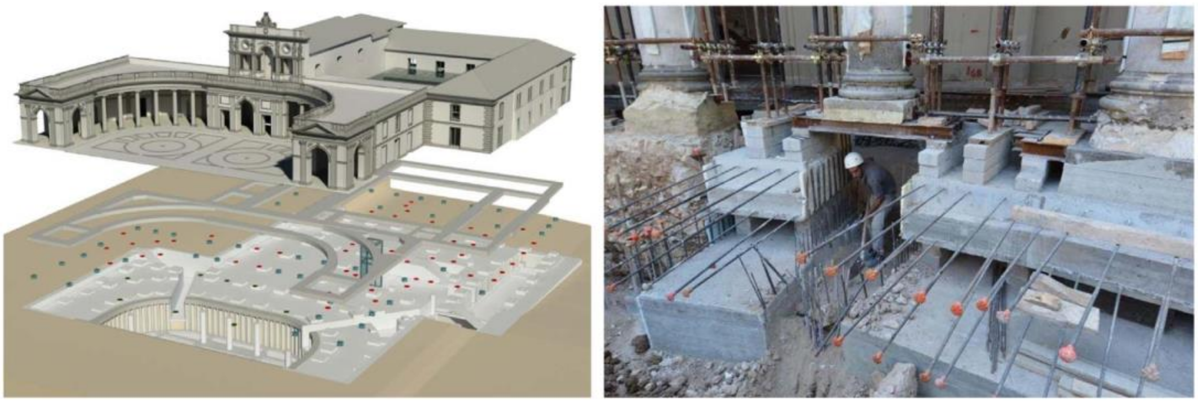

Figure 21. Emiciclo building at l'Aquila (courtesy of Somma and R. Vetturini)

Among other applications which were not reconstructions after earthquakes, it is worth mentioning the civic tower in Rieti, which was retrofitted by inserting a TMD at its top (Fig. 22). The old covering was first demolished and substituted by a new concrete slab, not connected to the perimeter walls, but supported by a steel structure with elastomeric isolators at its base.

Figure 22. TMD at the top of the Civic Tower in Rieti

Seismic rehabilitation of historical constructions is an important issue, especially in countries like Italy where these are highly vulnerable even against moderate seismic events, but also because of the daily presence of numerous tourists. Traditional techniques are not suitable and an adequate rehabilitation should guarantee the preservation of the original monument characteristics, identity and historical value. Therefore, the use of new technologies, such as seismic isolation, is advisable. Actually, this technique has already been used for retrofitting historical buildings in countries like the USA, Japan and New Zealand.

For seismic isolation of entire ancient buildings, a new system was developed by Clemente, De Stefano and Barla, called "Seismic Isolation Structure for Existing Buildings" (SISEB). It consists of an isolated platform to insert under the foundations of the building, without touching the building (Fig. 23). A discontinuity between the foundations and the soil is created by inserting horizontal pipes and positioning the isolation devices at their horizontal diametric plane. In order to facilitate successive placement operations, the pieces of pipe have a particular shape and are composed by two portions, the lower and the upper cylindrical sectors, respectively, which are connected by means of removable elements. Then, the building is separated from the surrounding soil, in order to allow horizontal displacements during an earthquake. So, the structure is seismically isolated, but not by means of interventions that could modify its architectural characteristics, which is very important for historical buildings. Even the underground levels are not modified, but can be part of the seismically protected structure.

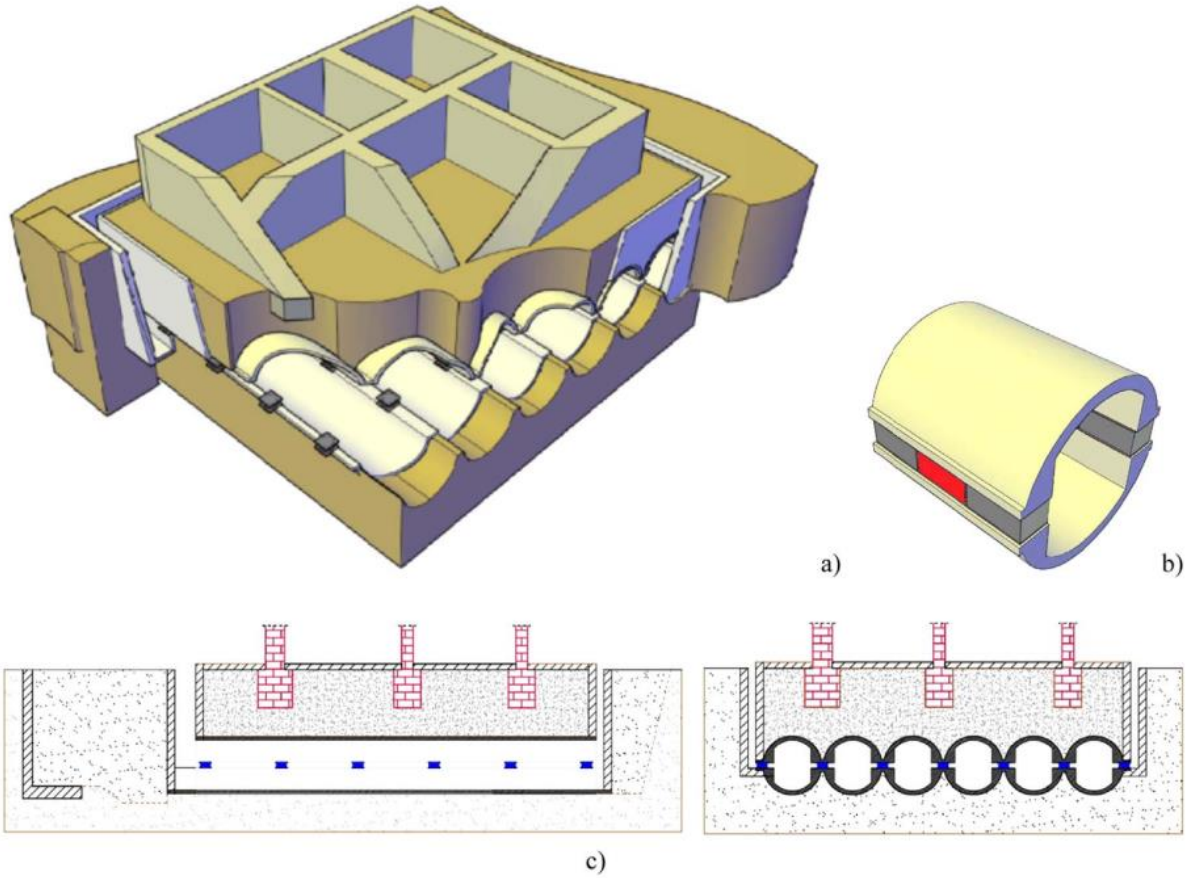

Figure 23. Seismic Isolation Structure for Existing Buildings, (a) view, (b) pipe element, (c) vertical sections.

The construction phases are the following:

- a trench is first excavated of at one side of the building and pipes are inserted by means of pipe jacking; the diameter of pipes should be ≥ 2 m, in order to allow the inspection and, if necessary, the replacement of the isolators.
- the connection elements placed at the positions of the isolators are removed, each pipe is joined to the adjacent ones and the isolators are positioned.
- the remaining connection elements are removed, so that the lower and upper cylindrical sectors are definitely separated.
- finally, vertical walls are built along the four sides of the building and the necessary gap is created.

Stiffening of the soil should also be done, preferably before the isolation operation. As mentioned, the sizes of the pipes must guarantee the accessibility and the possibility of replacing the devices. It is worthwhile reminding that the solution presents the advantage that the building and its architectural aspects are not altered, and neither are the underground levels. This is a very important requirement for historical and monumental structures. Two problems may arise during the micro-tunneling operations: soil settlement and vibrations induced at the surface level. The literature on the vibrations induced by pipe jacking is not very large and often not pertinent. Some indications come from analogous experiences supplied by large tunneling works or from vertical boreholes. These suggest that minor threats should be expected from induced vibrations; however, further theoretical and experimental studies are needed. More serious problems may arise due to settlements. A specific analysis was carried out with reference to a case study for which the mechanical properties of the ground were known with sufficient accuracy. A two-dimensional finite-element model was set up and then utilized in Diana software environment. This technique is certainly useful for historic constructions, but also for complex and industrial buildings.

It is stressed that anti-seismic devices may also be used to reconstruct cultural heritage buildings that have been fully destroyed by earthquakes. Obviously, this is not a retrofit operation, but the original materials (stones) can be used for the external walls, in order to preserve the original external appearance and features of the structure. In this case, the installation of anti-seismic devices is advisable, so as to avoid collapse in future earthquakes. An example of this kind was the reconstruction of the “Clock Tower” of the Castle of Gemona del Friuli, Udine, completed in 2016 (structural design by F. Cioppettini, acceptance certificate by A. Martelli). It had been fully destroyed by the already mentioned Friuli earthquakes of May and September 1976. An inner steel frame was inserted, which supports all floors and the roof bell. It was strengthened with Buckling Restraint Braces (BRADs), in order to limit its lateral deformation and prevent hammering against the external reconstructed masonry walls (from which it is separated by an adequate transverse gap).

7. Monitoring of Seismic Isolated Buildings

The most important base isolated buildings in several countries, such as Japan, USA and China, have been equipped by monitoring systems, which confirmed their excellent behavior under strong earthquakes. In Italy, a few seismic isolated buildings have already been provided with seismic monitoring systems. Two relevant cases are presented in the following, which point out the importance of analyzing the dynamic behavior of structures even under low magnitude seismic events.

7.1 The Jovine School in San Giuliano di Puglia

This structure, already described previously, was instrumented within the framework of a research project organized by ENEA in collaboration with the Italian National Civil Protection Department and the Municipality of San Giuliano di Puglia and funded by the

Office for the reconstruction of San Giuliano di Puglia. The site and the structure, comprising two buildings (the school and university, respectively) rising up from a unique base deck, were instrumented as shown in Fig. 24:

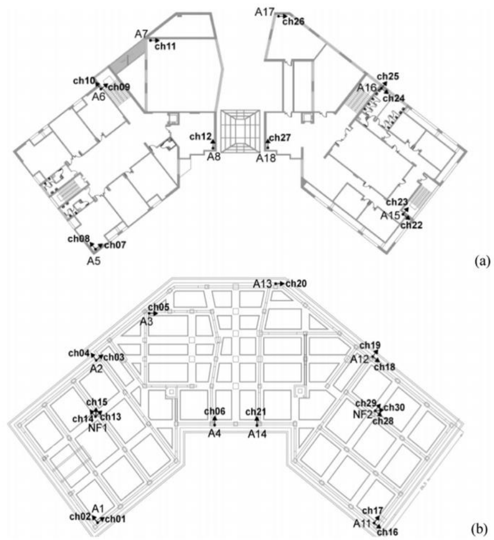

Figure 24. Sensor layout (a) on the roofs and (b) on the foundation (NF1 and NF2) and the deck just above the isolation layer

- Two triaxial sensors are deployed in the soil quite close to the building, one on the surface and another 30 m below the previous one; these allow measuring the seismic input and the soil amplification.
- Two triaxial accelerometer sensors were placed on the foundation, one under the school (NF1) and the other under the university center (NF2).
- Four biaxial accelerometer sensors (two at the school, CH01-CH02 and CH03-CH04, and two at the university center, CH16-CH17 and CH18-CH19) and four uniaxial accelerometers (two at the school, CH05 and CH06, and two at the university center, CH20 and CH21), were placed just above the isolation layer;

- Four biaxial accelerometer sensors (two at the school, CH07-CH08 and CH09-CH10, and two at the university center, CH22-CH23 and CH24-CH25) and four uniaxial accelerometers (two at the school, CH11 and CH12, and two at the university center, CH26 and CH27), were all placed on the roof of the two buildings.

Up to now, few seismic events of low magnitude have been recorded. The analysis of the dynamic response pointed out that the seismic isolation system was not activated during the earthquake. At any rate, some interesting features of the structure were pointed out. In Fig. 25, the acceleration time histories obtained at the foundation (CH13) and on the roof (CH07), respectively, during the earthquake that occurred on December 20th, 2013 (Ml = 3.8, epicenter distance = 11 km, depth = 25.7 km) are plotted. The maximum acceleration values were 1.7 cm/s2 at foundation and about 4.0 cm/s2 on the roof. The presence of the rubber isolators influenced the wave propagation pattern in the superstructure; furthermore, measurable shifts between the arrival of P waves in the vertical components at the NF1 and NF2 locations at the foundation were found (Fig. 26 a), as well as a significant shift between the arrival of P waves in the horizontal components at the foundation and the roof (Fig. 26 b). Three structural resonances were found, equal to 4.0, 4.2 and 5.8 Hz, respectively, all associated with vibration modes of the superstructure. The study of the particle motion at the different sensor locations revealed the deformability of the base deck, which could influence the structural behavior under strong earthquakes (Fig. 27).

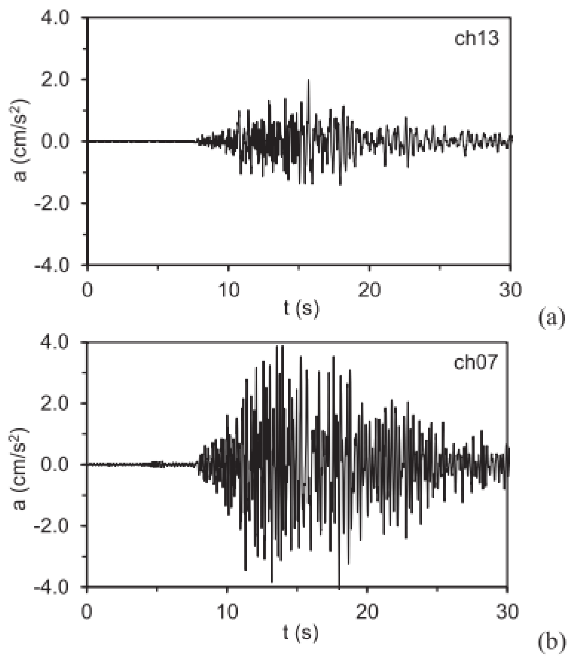

Figure 25. Acceleration time histories recorded (a) on the foundation and (b) on the roof in the horizontal direction

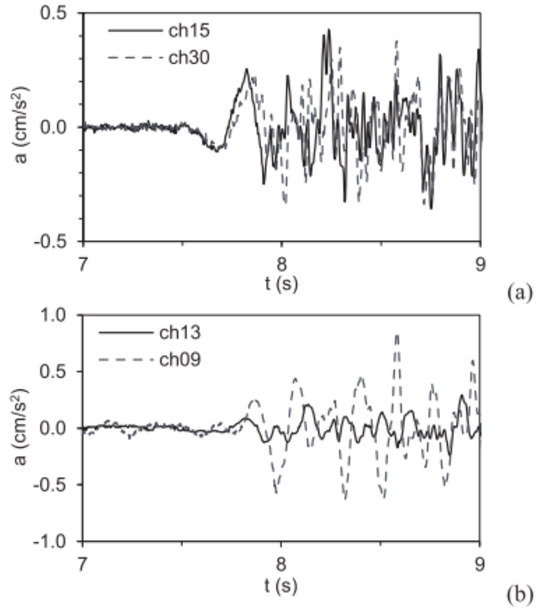

Figure 26. - (a) Arrival of P waves in the vertical components at the foundation, (b) Arrival of P waves in the horizontal components at the foundation and the roof of the school

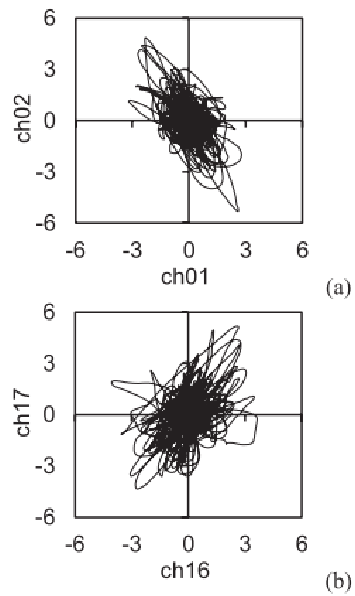

Figure 27. Particle acceleration (cm/s2) of the locations (a) ch01-ch02 on the base deck of the school and (b) ch16-ch17 on the base deck of the university.

7.2 The Operative Centre of the Umbria Civil Protection at Foligno

The Civil Protection Centre of the Umbria Region in Foligno has been equipped with a seismic monitoring system, within the framework of a research project organized by ENEA in collaboration with the Umbria Region. It is composed of twelve accelerometers, deployed in the building as follows (Fig. 28):

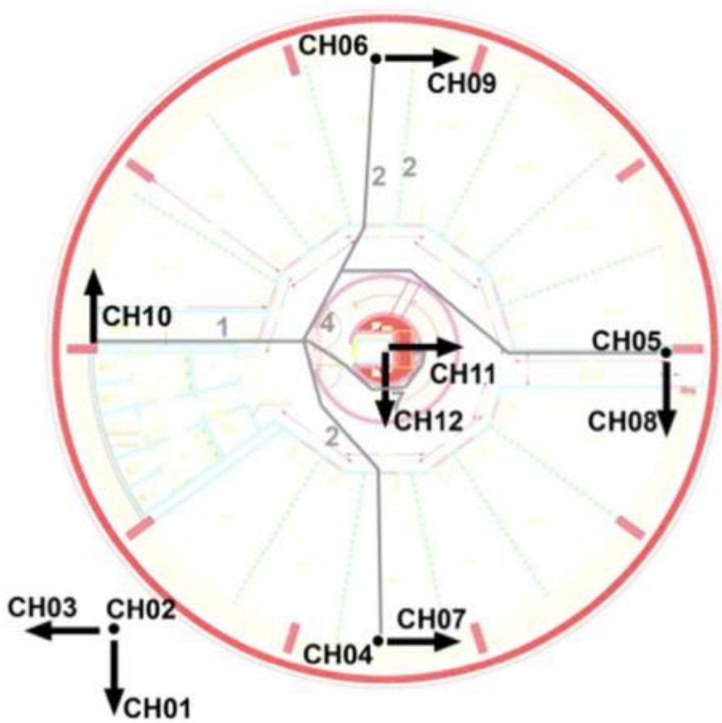

Figure 28. Seismic monitoring network in the Operative Centre of the Civil Protection

- Three accelerometers (CH01, CH02 and CH03) were placed at the basement, below the isolation system;
- Seven accelerometers were placed on the first floor, just above the isolation system: three of them in the vertical direction (CH04, CH05 and CH06), two in x direction (CH07 and CH09) and two in y direction (CH08 and CH10);
- Two accelerometers were placed at the top of the building in the center of the dome in the horizontal directions (CH11 in x direction, CH12 in y direction).

The monitoring system recorded all the events of the Central Italy seismic sequence that started on August 24th, 2016. In Fig. 29, the acceleration time histories recorded on the foundation, just above the isolation system and at the top of the building during the earthquake of October 30th, 2016 (M = 6.5, distance from epicenter = 36 km), are shown. The absence of any amplification is evident, as well as the presence of a significant change in the frequency content. This is also confirmed by the Fourier spectra (Fig. 30), in which a first resonance frequency at about 1 Hz is evident.

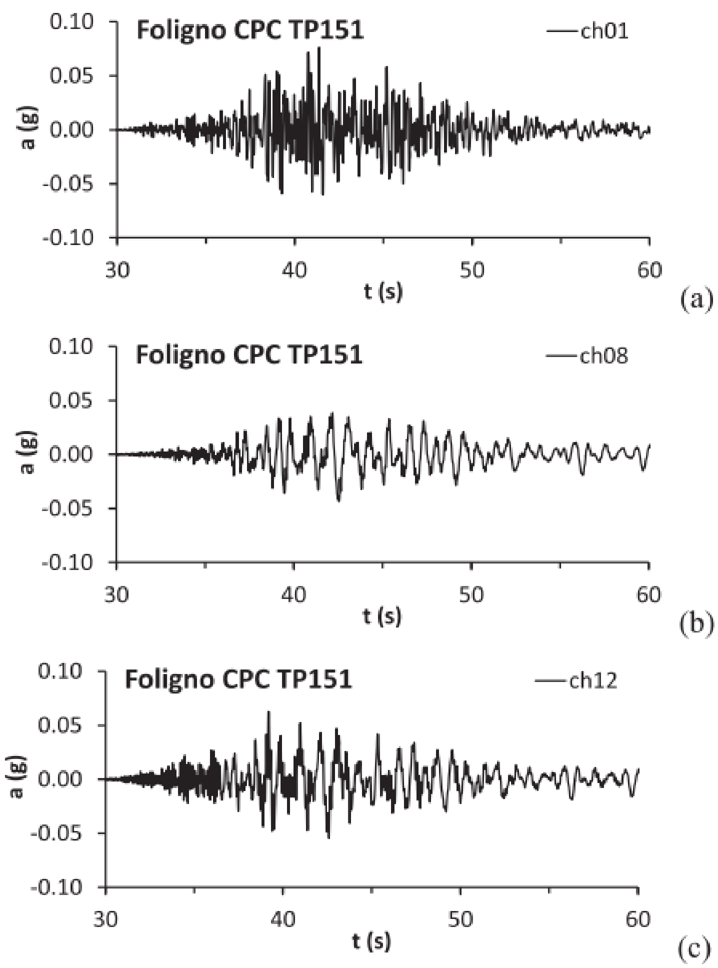

Figure 29. Time histories recorded (a) on the basement, (b) just above the isolation system

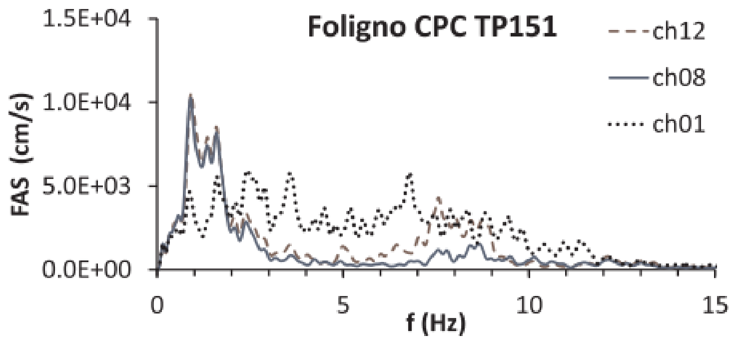

Figure 30. Fourier spectrum amplitude at different level

From the acceleration time histories, the displacement time histories were obtained by means of double integration. Fig. 31a shows that the relative displacement between the first floor and the basement was about 10 mm, while the drift between the top and the first floor was less than 5 mm (Fig. 31b), which is much lower than the limit value suggested by the code. Taking into account the variability of the shear modulus of the rubber with the shear deformation, the resonance frequency value is consistent with the measured relative displacements. It is worthwhile noting that in a traditional industrial building at the same site very high amplification was observed with a maximum acceleration at the top of about 0.4g.

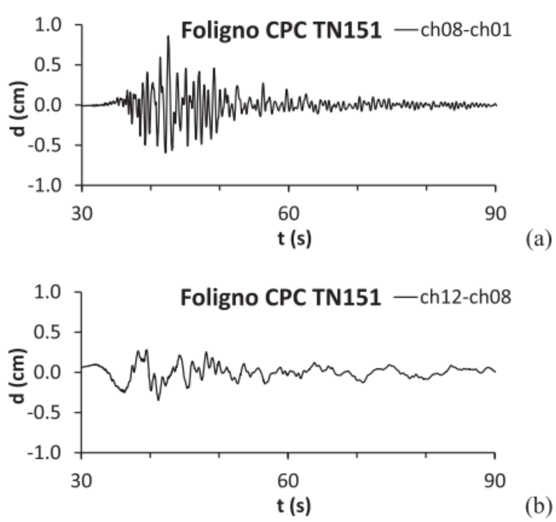

Figure 31. Relative displacement (a) between the first floor and the basement and (b) between the top and the first floor.

8. Types of Base Isolation Devices

In practice, the base system is often used in areas that are prone to seismic events. By using an additional layer of protection against these forces, this system can help to ensure safety. The base isolation system is a seismic protection technique that is designed to reduce the effects of earthquakes on buildings. Essentially, this system works by creating a physical separation between the super structure of a building and its foundation or sub structure (Fig. 32).

There are several different types of these devices that we use, each with its unique properties and benefits. The selection of the appropriate base isolation device will depend on factors such as the type of building, the location, and the level of protection required.

To achieve this goal, the base isolation system utilizes a variety of materials and techniques that are intended to absorb the energy of seismic waves. These materials can include rubber bearing, steel plates, and other specially designed to resist the forces of an earthquake.

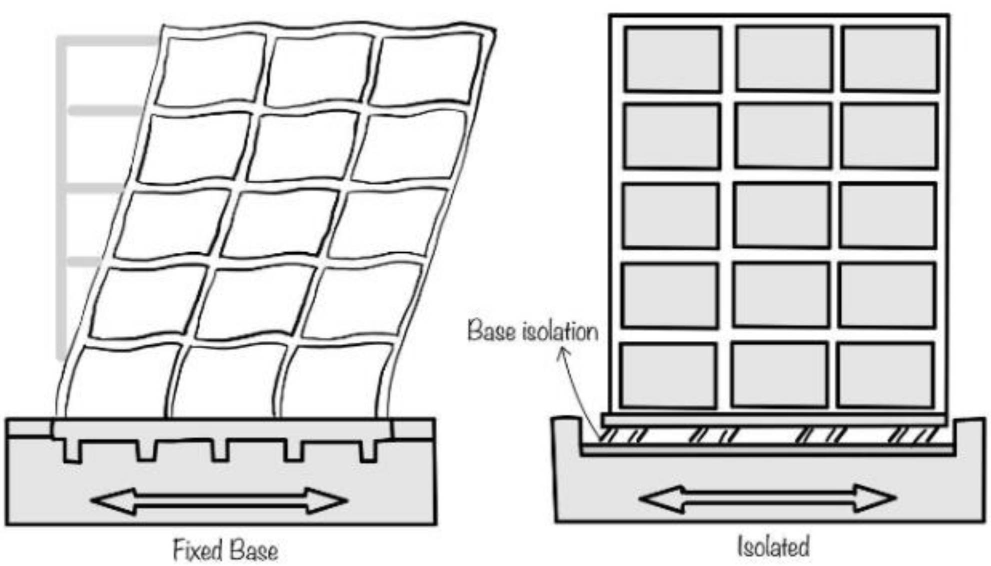

Figure 32. Fixed base versus Isolated

8.1 Rubber bearing

Rubber bearings are one of the most popular forms of base isolation devices. These bearings are of rubber and steel layers that combine to absorb the seismic wave energy. Rubber bearings are flexible and may have varying stiffness levels. This makes them appropriate for a wide variety of building types and seismic zones.

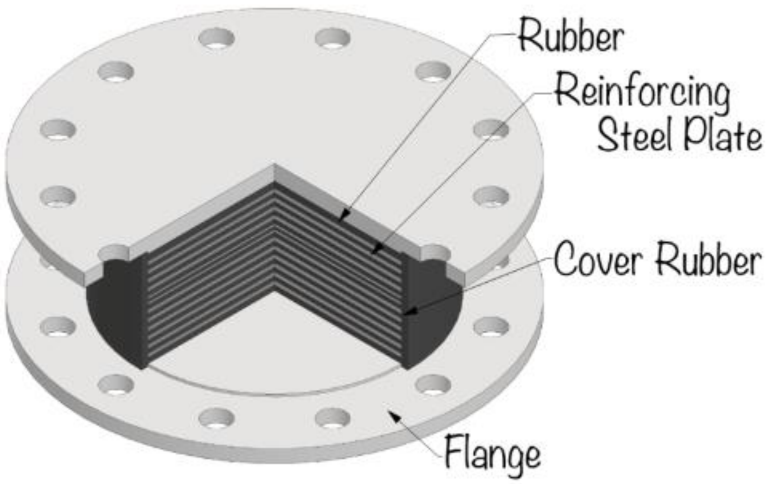

Figure 33. Rubber bearing

8.2 Lead-rubber bearing

Similar to rubber bearing, lead rubber bearing (Fig. 34) include a layer of lead encased within the rubber. This lead layer aids in boosting the bearing – dampening ability and may provide improved isolation in more seismically active areas. Lead-rubber bearing are a suitable option for structures that need long-term protection from seismic activity since they are more resilient than rubber bearing.

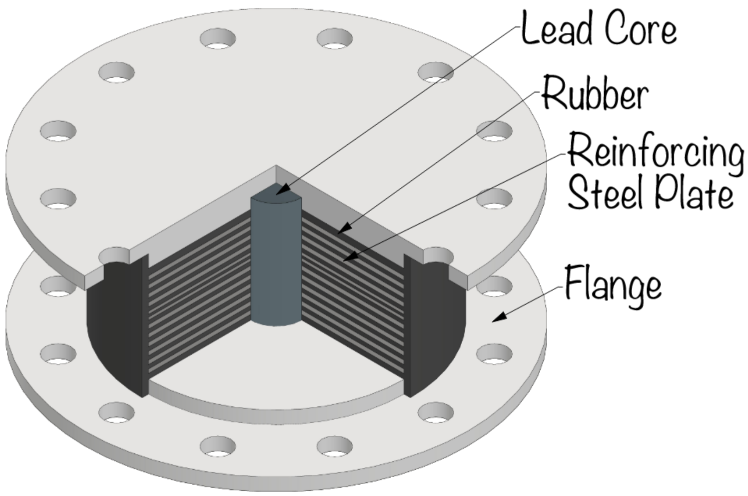

Figure 34. Lead rubber bearing

8.3 Friction pendulum bearing

Another base isolation technique is friction pendulum bearing (Fig. 35). These bearing shield the structure from seismic energy by using a pendulum. Typically, a steel ball that rests on a curved surface serves as a pendulum. The pendulum swings back and forth during an earthquake, dissipating the energy of the seismic waves.

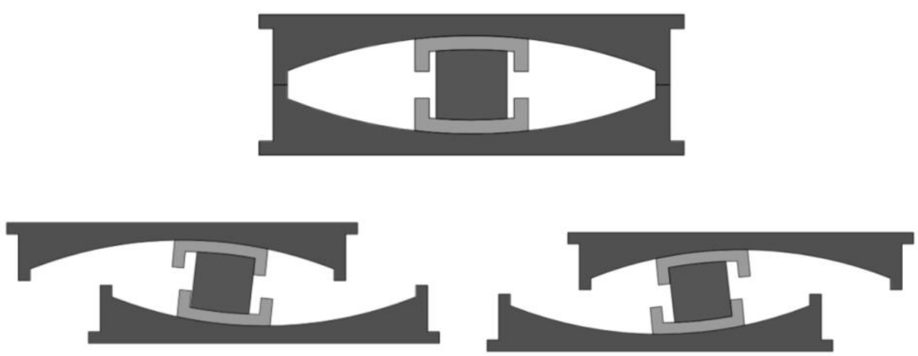

Figure 35. Friction pendulum bearing

9. The 10 Largest Base-Isolated Buildings in the World

9.1 Apple Park. Cupertino, California

Figure 36. Apple Park. Cupertino, California

Apple Park. Cupertino, California, 445,005 Square meters. Apple’s new corporate headquarters is a four-story, ring-shaped building, with a circumference of 1,512 sqft. It houses 12,000 employees and opened in April 2017. It was designed by Foster and Partners. In addition to the four floors above the ground, it also includes three stories below ground. The building sits on top of 700 base isolators. Each isolator is 7ft in diameter and weighs about 15,000 lbs. the isolators were customized for low friction, according to the lead structural engineer, John Worley, of Arup. Construction of the entire Apple Campus 2, including the headquarters building as well as a 1,000-seat auditorium (the Steve Jobs Theater), a wellness-fitness center, two R&D buildings, a visitor center and parking structures, totaled $5 billion. The building’s inner part is a 30-acre park, featuring fruit trees, winding paths and a pond.

9.2 Adana Integrated Health Campus, Adana, Turkey

Figure 37. Adana Integrated Health Campus, Adana, Turkey

Adana Integrated Health Campus, Adana, Turkey, 430,000 square meters. The campus was developed as a public-private partnership between ADN PPP Sağlik Yatirim A.Ş., a joint venture of four firms, and the Turkish Ministry of Health. The campus will have a total capacity of 1,550 beds housed in three hospitals: the 1,300-bed main hospital, a 150-bed physical-therapy and rehabilitation hospital and a 100-bed high-security criminal psychiatric hospital. The campus is supported by 1,512 base The complex was designed HWP, and built by Rönesans Sağlik Yatirim. The structural engineer was Ulker Engineering Ltd. It was completed in May, 2017.

9.3 Tokyo Skytree East Tower, Tokyo

Figure 38. Tokyo Skytree East Tower, Tokyo

Tokyo Skytree East Tower, Tokyo, 229,237 square meters. This mixed-use complex includes an office tower, mall and entertainment complex. An eight-story podium contains a shopping center, planetarium and theater serving millions of tourists visiting the observatories on the adjacent Tokyo Skytree tower. The office tower rises to 31 stories. The complex was designed by Nikken Sekkei and built by Obayashi Corp. It was completed in 2012.

9.4 Isparta City Hospital, Isparta, Turkey

Figure 39. Isparta City Hospital, Isparta, Turkey

Isparta City Hospital, Isparta, Turkey, 221,000 square meters. Akfen Holding, a Turkish conglomerate, built the hospital as part of a 25-year public private partnership with the Turkish Ministry of Health. Dost Insaat ve Proje Yonetimi A.S. served as the design-builder of the 755-bed facility, with architectural firm Yazgan Mimarlik & Hayalgucu Mimarlik J.V. Handling the design work. The base isolation system features 903 surface-friction-slider units supplied by Maurer AG. The project's structural engineer was Probi Insaat Proje Bilgi Islem Merkezi A.S. It was completed in December 2016.

9.5 Logistics Park Hino, Tokyo

Figure 40. Logistics Park Hino, Tokyo

Logistics Park Hino, Tokyo, 212,853 square meters. A five-level warehouse with spiral ramps at both ends, it was designed by Obayashigumi Design Office and built by the Obayashi Corp. it was completed in 2015. It is owned by Mitsui Fudosan Co., Ltd.

9.6 Logiport Sagamihara, Sagamihara, Japan

Figure 41. Logiport Sagamihara, Sagamihara, Japan

Logiport Sagamihara, Sagamihara, Japan, 210,000 square meters. A five-level warehouse with spiral ramps at both ends, it was designed by Obayashigumi Design Office and built by the Obayashi Corp. It was completed in 2013. Sagamihara is a western suburb of Tokyo.

9.7 Shinagawa Season Terrace, Tokyo

Figure 42. Shinagawa Season Terrace, Tokyo

Shinagawa Season Terrace, Tokyo, 205,786 square meters. An office building, it was designed by the NTT Facilities Design Office and built by Taisei Corp. It was completed in 2015.

9.8 Sabiha Gökçen Airport International Terminal, Istanbul

Figure 43. Sabiha Gökçen Airport International Terminal, Istanbul

Sabiha Gökçen Airport International Terminal, Istanbul 200,000 square meters. ISG, a partnership of Limak Holding (LIMAK), GMR Infrastructure Limited (GMR) and Malaysia Airports Holdings Berhad (MAHB) is the operator of the airport under a 20-year build-operate-transfer agreement signed in 2008. Tasked with completing the terminal in 18 months, Limak and GMR formed a joint venture and signed an EPC contract with ISG. The building's footprint is 160 m x 272 m and includes four stories above a basement level. It can serve 16 middle-sized fuselage aircraft or eight wide-body planes simultaneously. It features seven arched bays with vaulting roofs of alternating 32-m and 48-m spans, employing space frame trusses. The superstructure is a steel moment frame, resting on 292 triple-friction-pendulum Isolation bearings supplied by Earthquake Protection Systems, Inc. The structural engineer who led the seismic design for the terminal was Atila Zekloglu, of Arup. The terminal opened in 2009.

9.9 Erzurum Regional Research and Training Hospital, Erzurum, Turkey

Figure 44. Erzurum Regional Research and Training Hospital, Erzurum, Turkey

Erzurum Regional Research and Training Hospital, Erzurum, Turkey 180,000 square meters. It was built by Kur Construction Co. Ltd. This 400-bed hospital is supported by 386 lead-rubber bearing isolators, which were supplied by Dynamic Isolation Systems Inc.

9.10 Tan Tzu Medical Center, Tai Chung, Taiwan

Figure 45. Tan Tzu Medical Center, Tai Chung, Taiwan

Tan Tzu Medical Center, Tai Chung, Taiwan, 157,930 square meters. Designed by C.C. Hsu & Associates, the complex includes a four- to six-story western section, a 17-story tower, and two underground levels containing parking, storage space and a cafeteria. The 1,300-bed medical center rests on 325 lead-rubber-bearing base isolators located below the second underground level. The building also is outfitted with 88 fluid viscous dampers. The lateral-force-resisting system of the superstructure consists of steel-reinforced-concrete moment frames. The total superstructure mass resting on the base-isolation system weighs 285,600 tons. The base-isolation system was designed by KPFF consulting engineers, led by Andrew W. Taylor. Construction was completed in 2006, at which time the structure was the largest base-isolated building in the world. The project was challenging, as the building is located only 400 m from the Chelungpu fault, which ruptured in the 1999 Chi-Chi earthquake.

10. Conclusions

A state-of-the-art on seismic isolation and its most important applications have been presented in this course, pointing out that this technology is now mature to be used as the standard anti-seismic system to adequately protect structures against strong earthquakes all over the world. Actually, the number of applications has increased remarkably in the last years, not only for strategic buildings, but also for residential buildings.

In early applications to buildings in Italy, HDRBs and LRBs were used in parallel with SDs, in order to optimize the dynamic behavior of the isolated structure. CSSs were introduced only in 2009, after the L′Aquila earthquake, but their application became very common rapidly. It is worthwhile reminding that all devices in Italy are designed and tested according to the norms EN 15129:2009, which have made the CE marking compulsory since August 2011.

The number of retrofits of existing buildings with seismic isolation *has* increased remarkably. The most interesting applications on reinforced concrete, masonry and historic structures have been shown, pointing out the specific issues for each case. Unfortunately, most applications are in areas recently hit by seismic events, and are part of the reconstruction works, while a comprehensive project for seismic damage prevention finds difficulties in covering in the entire country.

Finally, the recordings obtained during the seismic sequence that has shocked Central Italy since August 24th, 2016, have been presented and discussed, pointing out that the behavior of isolation devices can be quite different under low magnitude earthquakes. These occurrences should be further analyzed in detail, comparing the results obtained during seismic events of different magnitudes and epicenter distances, which can produce effects quite different at a site in terms of energy and frequency content of the motion transmitted to the structures.

Experimental analyses on isolation devices and base isolated building are necessary for future developments, as well as the seismic monitoring of seismically isolated structures.

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