State-of-the-art of development and application of anti-seismic systems in Italy

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ABSTRACT: Some tens of thousands of structures have already been protected by passive anti-seismic (AS) systems in over 30 countries, mainly by the seismic isolation (SI) and energy dissipation (ED) ones. Their use is going on increasing everywhere, although its extent is strongly influenced by earthquake lessons and the features of the design rules used. Applications have already been made to both new and existing civil and industrial structures of all kinds. In some countries (unfortunately not so much in Italy), they include some High Risk (HR) plants. In a civil context, they already concern not only strategic and public structures, but also residential buildings. In Italy, the AS systems have become more and more popular especially after the 2009 *Abruzzo* earthquake. This paper focuses on the development and application of such systems in the aforesaid country, by devoting particular attention to SI (especially) and ED of buildings. Moreover, it outlines the benefits of SI for ensuring the indispensable absolute integrity of strategic and public structures and cultural heritage, as well as those of the AS systems, in general, for retrofits and reconstruction. Finally, some remarks are provided on the costs of SI and on the conditions for the correct use of this technique.

1 INTRODUCTION

The traditional anti-seismic (AS) design aims at protecting human life, to keep damage to a low level and strategic structures full operational even immediately after earthquakes. So, seismic codes require that no damage occurs under low to medium intensity earthquakes, while, in case of strong earthquakes, the only requirement is to avoid collapse, but even heavy damage is allowed. On the basis of this concept, the elastic spectrum, which concerns the actual seismic accelerations of the structures, is modified so as to obtain the design spectrum. Here the actual seismic accelerations are reduced by means of the behavior factor q, which depends on the capacity of the structure to dissipate energy during the earthquake; it can be very high (up to $4 \div 5$) if the structure is able to be damaged in a smart way, i.e., by involving several elements and avoiding collapse. This principle turned to be not economically sustainable: think not only of the repair and reconstruction costs, but also of strategic structures (such as buildings devoted to civil protection activities, important bridges and viaducts, hospitals, etc.), which should keep fully operational during and immediately after even strong earthquakes, and of High Risk (HR) plants and components (e.g., nuclear power plants, other nuclear facilities and some chemical installations or components too), which should satisfy very high safety requirements.

The previous concept is overpassed by the AS systems, which are based on a drastic reduction of the energy that the soil transmits to the structure, instead of relying on its resistance (seismic isolation, or SI), or on the insertion of special devices inside the structure (e.g., of dampers, which “attract” the seismic energy on themselves and dissipate it), so that the structure itself becomes less vulnerable to earthquakes. When using SI, this result is obtained by increasing the fundamental period of vibration of the structure.

Nowadays, SI and the other AS systems are ready for a wide application all over the world, to adequately protect structures even against strong earthquakes. In fact, the number of structures protected by AS systems increased remarkably in the last years, so that, nowadays, a complete list of them is impossible in practice. As stressed by Clemente and Martelli (2017) and Martelli ed. (2017), reliable data were available until 2014, when more than 24,000 structures, located in more than 30 countries, were protected by passive AS systems, such as the SI or energy dissipation (ED) ones, or those formed by Shape Memory Alloy Devices (SMADs) or Shock Transmitter Units (STUs). Such structures concern both new constructions and retrofits of existing ones of different types: bridges and viaducts, civil and industrial buildings, cultural heritage structures and industrial components and installations, including HR nuclear and chemical plants and components. The structures protected by the AS systems are reinforced concrete (r.c.), masonry, steel or wood constructions. Japan is the leading country for the total number of applications of the AS systems; it is followed by the People Republic (P.R.) of China, the USA, the Russian Federation and Italy, where the use of the AS systems increased significantly after the 2009 *Abruzzo* earthquake (Clemente & Martelli 2017, Martelli ed. 2017).

In the civil context, the AS systems are applied not only to strategic structures (civil defence centres, hospitals, etc.) and to relevant public structures (schools, churches, museums, shopping malls, hotels, airports, etc.), but also to residential buildings and even to small and light houses. The number of applications is increasing everywhere, but especially in the areas that were recently hit by earthquakes.

Most SI systems rely on the use of Rubber Bearings (RBs), especially the High Damping natural Rubber Bearings (HDRBs) and Lead Rubber Bearings (LRBs), but also on that of Neoprene Bearings (NBs), and, especially in Japan, Low Damping Rubber Bearings (LDRBs) in parallel with dampers. In buildings, plane surfaces steel-PTFE Sliding Devices (SDs) are often used in parallel to the RBs, mainly with two purposes: (a) to support the light parts of structures without uselessly stiffening the SI system, which would make it less effective; (b) to optimize the structure dynamic behaviour, by minimizing the torsion effects (i.e., in order to have the first two vibration modes as translational ones, even in buildings that are significantly asymmetric in the horizontal plane).

For the reconstruction following the 2009 *Abruzzo* earthquake and afterwards, also Curved Surface Sliders (CSSs), derived from the US Friction Pendulum Systems (FPS) and the subsequent German Seismic Isolation Pendulum (SIP), have been widely used in Italy too. Finally, rolling isolators (in particular ball or sphere bearings) must be reminded. They are very effective and there are several applications to protect buildings in Japan, but not in many other countries (including Italy), because of their large cost; however, they have already been used, even in Italy, to protect some precious masterpieces, cases in museums and costly equipment, including operating-rooms in hospitals.

It shall be stressed that AS systems represent the only way to adequately protect buildings and their contents, as well as infrastructures and industrial plants, by avoiding environmental disasters and economic losses. Furthermore, all structures protected by RBs located in areas hit by even severe earthquakes exhibited an excellent behaviour, in spite of the fact that, in some cases, they had been designed based on earthquake levels which were much lower than those really occurred (Martelli 2017).

2 APPLICATION OF THE ANTI-SEISMIC SYSTEMS IN ITALY

As mentioned, Italy is the fifth country in the world and the first in Western Europe for the overall number of applications of the passive AS devices (Clemente & Martelli 2017, Martelli 2017). The use of the AS systems started in 1975 for bridges (for the Somplago viaduct) and in 1981 for buildings (for two strategic buildings in Naples, designed by F.M. Mazzolani). A significant application was the Telecom Italia building in Ancona, designed by G.C. Giuliani and certified as safe by A. Martelli in 1992 (the latter was even successfully subjected to release tests, as shown by Giuliani, 2017).

In spite of the aforesaid pioneering role of Italy in the development and application of passive AS systems, their use remained rather limited, due to the lack of design rules, till 1998, then due to the very complicated and time-consuming approval process (Clemente & Martelli 2017, Martelli 2017). So, significant applications of passive AS systems restarted in Italy only after the 2002 *Molise* and *Puglia* earthquake, during which the Francesco Jovine primary school of San Giuliano di Puglia collapsed, by killing all the youngest children. After that disaster, a new national seismic code was set up, which simplified the use of the AS systems. The new Francesco Jovine school (Fig. 1) was the first school in Italy to be protected by SI. The structure is composed by two buildings rising up from an unique base deck, which represents a sort of artificial ground, protected by 61 HDRBs and 13 SDs. It was designed with the cooperation (for the assessment of the seismically isolated configuration) of a team composed by P. Clemente (coordinator), G. Buffarini, M. Dolce and A. Parducci; the structure was certified as safe by A. Martelli in 2008 (Clemente & Martelli 2017, Martelli 2017).

After the aforesaid earthquake, the application of SI regarded mainly further school buildings (some of which were certified as safe by A. Martelli) and strategic structures (Clemente & Martelli 2017). Among the latter, it is worthwhile citing the new Civil Protection Centre of Umbria Region in Foligno, in which several buildings have been protected by means of SI systems. Most of them were designed by A. Parducci, while P. Clemente coordinated the team of ENEA experts who analysed and approved the project, on behalf of Umbria Region, and also carried out a detailed local seismic response analysis. The building that hosts the Operative Centre has a very interesting architectural design, with a hemispherical shape (Fig. 2); it is 22 m high and its base diameter is about 31 m. The 10 isolators, deployed along the perimeter, are HDRBs (diameter = 1 m, horizontal stiffness = 1,310 kN/m, damping factor = 10%), which determines a fundamental frequency of the isolated structure of about 0.38 Hz; it was certified as safe by A. Martelli in 2011.

The Civil Protection Centre of Umbria Region in Foligno has been equipped with a seismic monitoring system (developed with the collaboration of ENEA), which plaid an important role in recording data during the earthquakes that began affecting Central Italy on August 24, 2016 (Martelli 2017).

Fig. 1: The new base isolated Jovine school in San Giuliano di Puglia and view of some isolators.

Fig. 2: The Operative Centre of the Civil Protection Department in Foligno
during construction and after its completion.

The use of SI increased rapidly after the *Abruzzo* earthquake of April 6, 2009, as a consequence of not only the large damage caused by this event to conventionally founded buildings and cultural heritage, but also thanks to the use of such a protection system to buildings for temporarily hosting about 13,000 homeless residents (C.A.S.E. project). These consisted in 184 wood, r.c, steel, or wood pre-fabricated houses, each placed on a large isolated a r.c. slab supported by CSSs, manufactured in Italy, installed at the top of columns (Clemente & Martelli 2017).

Afterwards, SI has been largely used for 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 the 2009 earthquake to more than 400 in 2013. Several further applications to new-built and retrofitted structures were completed later or are now in progress, in other Italian areas too; a further incentive to the use of SI for reconstructions (where the soil quality is adequate) was also the 2012 *Emilia* earthquake (Clemente & Martelli 2017, Martelli ed. 2017).

It is noted that, also in Italy, SI has been used for masonry buildings too and that its application is going on for bridges and viaducts (which were at least 250 in 2009); moreover, it has already been used for protecting cultural heritage structures and single masterpieces (Clemente & Martelli 2017, Sorace & Terenzi 2017, Martelli 2017).

3 SEISMIC ISOLATION OF EXISTING AND CULTURAL HERITAGE STRUCTURES

3.1 Reinforced concrete buildings

There are mainly two types of interventions by means of SI for existing r.c. buildings: (a) cutting and elimination of a portion of the columns at a certain height in the first floor, and successive insertion of the SI devices; (b) insertion of the devices under the foundations and realization of a new sub-foundation (Clemente & Martelli 2017, Martelli ed. 2017).

Among the applications of the first type we remind a residential building in Tigli Street at Pianola, L'Aquila (Fig. 3), which had been severely damaged by the 2009 earthquake. The building was composed of three separated blocks and had been completed just before the *Abruzzo* earthquake. The blocks were first analysed also by means of experimental dynamic analysis, which identified the dynamic characteristics of the blocks; then the three blocks were joined at the first floor and SI devices were inserted at the top of the columns in the underground floor. The building was certified as safe by A. Martelli in 2014. An inspection carried out by him after the *Amatrice* earthquake of August 24, 2016 (moment magnitude M_W = 6,0) showed that the building had behaved very well, in spite of the non-excellent quality of the soil, with a maximum displacement of about 10 mm (Martelli 2017).

Fig. 3: The r.c. buildings at Pianola, L'Aquila (the new unique base deck and two isolators).

The second technique was applied, for the first time in Western Europe, to the residential building in Latini Street in Fabriano, Italy (Fig. 4). This building had been damaged (although mainly non-structurally) by the 1997-98 *Marche* and *Umbria* earthquake. New plinths were built under the existing ones and the SI devices were inserted between them. The building was certified as safe by A. Martelli in 2006. Also this building was affected by the recent earthquakes in Central Italy, and did not suffer any damage at all, contrary to some others in the same area, also reconstructed after the 1997-98

Umbria and *March*e seismic sequence, as verified by A. Martelli during an inspection he performed after the $M_W = 6.5$ *Norcia* earthquake of October 31, 2016 (Martelli 2017).

Fig. 4: R.c. building in Latini Street in Fabriano after completion, with view of the isolators and some piping (courtesy of G. Mancinelli, see Martelli, 2017).

3.2 Masonry buildings

As to the use of SI for retrofitting masonry buildings, recent applications have been listed by Castellano *et al.* (2017), together with those to r.c. structures. Examples were also given by Vetturini and Cecchini (2016), as shown by Figure 5.

Fig. 5: Valuable private residential buildings retrofitted in L'Aquila using SI (courtesy of R. Vetturini).

3.3 Cultural heritage buildings

The seismic rehabilitation of historical constructions is an important issue, especially in countries like Italy, due to their usual high vulnerability even in case of moderate events, but also to their historical importance and to the daily presence of many tourists. Traditional techniques are not suitable and an adequate rehabilitation should guarantee the preservation of the original monumental characteristics, identity and historical value. Therefore, the use of new technologies, such as SI, is advisable. Actually, this technique has already been used for retrofitting historical buildings in some countries (USA, Japan, New Zealand), but not yet in Italy (Clemente & Martelli 2017, Martelli 2017). In Italy, however, SI was already used (as mentioned) to isolate some precious single masterpieces, while applications to ancient buildings were performed by means of other kind devices (SMADs, STUs and dampers): for instance to the retrofit of the Upper Basilica of St. Francis in Assisi (which had been severely damaged by the 1997-98 *Marche* and *Umbria* earthquake and where both SMADs and STUs were installed), and, afterwards, to those of other churches and a few bell towers (Martelli 2017).

For SI of entire ancient buildings, a novel system was developed and patented in Italy, by P. Clemente and A. De Stefano, which foresees the installation of isolators in a sub-foundation (Clemente & Martelli 2017). This is the so-called "Seismic Isolation Structure for Existing Buildings" (SISEB); it consists in an isolated platform under the foundations of the building, which does not touch it (Fig. 6). A discontinuity between the foundations and the soil is created by means of the insertion of horizontal pipes and the positioning of SI devices at their horizontal diametric plane. In order to facilitate the successive 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 (Fig. 6). Then, the building is separated from the surrounding soil, in order to enable the horizontal displacements required by the SI system. So the structure is seismically isolated, but not interested by 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. More precisely, as mentioned by Clemente and Martelli (2017), the construction phases are the following: (a) 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 for the inspection of the isolators; (b) the connection elements placed in correspondence of the isolators are removed and each pipe is joined with the two adjacent ones, for example by means of a r.c. elements; (c) the isolators are positioned and the upper adjacent sectors are connected in correspondence of them; (d) afterword, also the other connection elements are removed, so that the lower and upper cylindrical sectors are definitely separated; (e) finally, vertical walls are built along the four sides of the building and a rigid connection, a r.c. slab or other, is realized between the building and the SI system. Stiffening of the soil can also be considered.

The sizes of the pipes must guarantee the accessibility and the possibility to replace the devices. It is worthwhile reminding that the solution presents the advantage that the building and its architectural aspect are not changed and so are the underground levels; this is a very important requirement for historical and monumental structures.

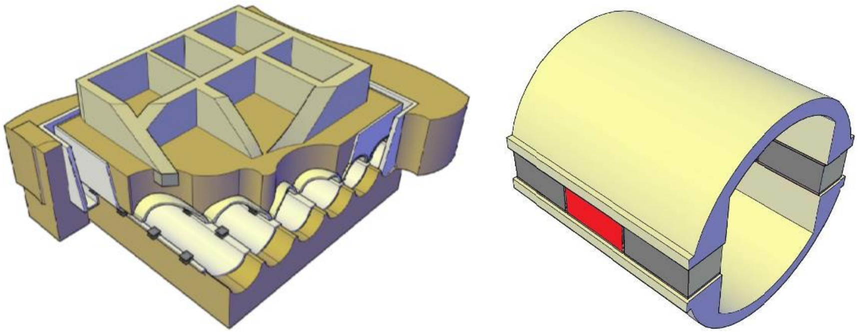

Fig. 6: Seismic Isolation Structure for Existing Buildings (view and pieces of pipe with a particular shape).

Two problems may arise during the micro-tunnelling operations: soil settlement and vibrations induced at the surface level. The literature related to the vibrations induced by pipe jacking is not very ample and often not strictly pertinent. Some indications can come from analogous experiences supplied by large tunnelling works or from vertical boreholes, which suggest that minor threats should be expected from induced vibrations; however, deeper 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 finite-element 2D model was set up and then exploited in *Diana 2* environment (Clemente & Martelli 2017). Settlements lower than 10 mm were evaluated, based in this study.

4 RECONSTRUCTION OF CULTURAL HERITAGE BUILDINGS USING AS DEVICES

It is stressed that AS devices may also be used to reconstruct cultural heritage buildings that have been fully destroyed by earthquake. Obviously, this is not a retrofit and the only possibility is to use the original materials (stones) in the external parts, in order to respect the original external appearance and features of the building, but the installation of AS devices is advisable, so as to avoid its new collapse in a future earthquake. An example of this kind of application was recently completed for the reconstruction of the so-called “Clock Tower” of the Castle of Gemona del Friuli (Udine), which was fully destroyed by the two *Friuli* earthquakes of May and September 1976. In this application (Fig. 7), an inner steel frame was inserted, which supports all floors and the roof bell and was provided by Buckling Restraint Braces (BRADs), in order to limit its lateral deformation, so as to hinder hammering against the external reconstructed masonry walls (from which it is separated by an adequate transverse gap). The two reconstructed buildings of the Castle were certified as safe by A. Martelli in 2015 and 2016 (Martelli 2017).

Obviously, other AS device types may be used too, for similar reconstructions (e.g., on a seismically isolated r.c. slabs supporting one or more reconstructed buildings, namely acting as “artificial grounds”). Various options of this kind may be considered for the reconstruction in the towns destroyed by the earthquakes that have struck Central Italy since August 24, 2016.

Fig. 7: The Castle of Gemona del Friuli before the 1976 earthquakes; collapse of its “Clock Tower” after the May event and (almost totally) after that of September; reconstruction of the tower, completed in 2015 with the original stones in its external part and an inner steel frame perovided with 22 BRBs.

5 COSTS OF SEISMIC ISOLATION

In the codes of some countries, like Japan, USA and Chile, SI is considered as a safety measure additional to the conventional design; consequently, its use introduces additional construction costs. Nevertheless, SI is being widely adopted in Japan, due to high level of perception of the seismic risk and to the very frequent strong earthquakes in this country (Clemente & Martelli 2017, Martelli 2017).

The aforesaid level of perception is much lower elsewhere. Thus, in order to encourage the application of this technique, in other countries (for example, in Italy, P.R. China and Armenia) the seismic codes allow for considering the actual reduction of the seismic forces acting on the superstructure when SI is used. This limits or even balances the additional construction costs entailed by the use of SI. With reference to the design according to the Italian code, the difference between the cost of a building designed with a fixed base and that of the same building designed with base SI is very low. Differences are certainly negligible for buildings designed to support very large earthquakes, but also for low intensity earthquakes the choice of base SI is obviously justified, especially for irregular and special buildings. In this last case, the solution with base SI could be even less expensive. Besides, we should take into account the different useful area due to the smaller size of pillars in the solution with base SI, which translates in a different value of the building. These considerations were verified after most of the already mentioned applications in Italy, designed or certified as safe by the authors.

Finally, the use of SI is certainly suitable if we refer the comparison to the life time of the building. In fact, seismic isolated buildings will not suffer loss of functionality or need for repair works, even after strong earthquakes.

6 RECOMMEDATIONS FOT CORRECT USE OF THE ANTI-SEISMIC SYSTEMS

Obviously, when the safety of the entire structure and its content, including human lives, is entrusted to a certain number of devices, a higher level of safety is required for them (Clemente & Martelli 2017, Martelli 2017). This means assuming, in the structural design, values of the seismic acceleration higher than those adopted for traditional structures. It is worthwhile noting that, when using SI, it should be recommended (and this is possible from both a technical and an economic point of view) to consider the seismic input associated to a very low probability of exceedance (for example, 2% in 50 years), according to the probabilistic approach, or to the Maximum Credible Event (according to the deterministic approach). Anyway, this is not enough: a great care must be devoted to the selection of the characteristics of the devices, their qualification, production quality, acceptance tests, installation, protection, maintenance and check that their design features remain unchanged during the entire life of the structure. Furthermore, some important construction details, such as structural gaps, interface elements for pipes, cables, stairs and lifts, must be well designed, realized in practice and controlled during their life time. Finally, the installation of a suitable seismic monitoring system is recommended, as stressed by Clemente and Martelli (2017), Martelli ed. (2017), De Stefano (2017) and other papers presented at this conference. Obviously, the safety requirements are more restrictive for HR plants (Clemente & Martelli 2017, Poggianti *et al.* 2017).

7 CONCLUSIONS

SI and the other AS systems are ready for a much wider application to adequately protect structures even against strong earthquakes, not only in Italy, but worldwide. Especially SI is already considered as the best solution for structures for which a high safety is required. These are important for public buildings, such as schools and other crowded public constructions (also because the large vibration period values of an isolated superstructure minimize panic) and for strategic structures (for which the full integrity and operability after even violent earthquakes shall be guaranteed). The challenge for the next future is to consider SI as the usual anti-seismic technique for residential buildings too. In order to pursue this objective, the correct applications of SI should be guaranteed, thanks not only to a good knowledge of this techniques and the concerned design rules, but also to suitable controls and the guarantee that the isolators keep their design features unchanged all during the structure useful life. However, at least in Italy, a much higher level of perception of the seismic risk by both public opinion and Institutions is also necessary.

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