MODERN SEISMIC PROTECTION SYSTEMS FOR CIVIL AND INDUSTRIAL STRUCTURES

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Abstract

The limits of the conventional fixed-base seismic design of structures are stressed, together with the capability of the modern seismic vibration passive control (SVPC) techniques to overcome such limits, for both new and existing constructions. The main features of such techniques (seismic isolation, energy dissipation and those using shock transmitters and shape memory alloys) are summarized. The history and worldwide state-of-the-art on their application is reported, especially for buildings, focusing on the most recent achievements and based on very recent information mainly provided by a just published book and reviews written by the author of this paper. The SVPC systems that are the most popular in the various countries are mentioned, together with future trends. In particular, details are given on the history of application of the such systems in Italy, which is the author homeland, to stress the leadership it achieved in the development and application of the SVPC systems at European level and the contribution provided by ENEA, as well as the key role plaid by the availability and features of specific design rules on the success of the SVPC systems. Such a key role has also been confirmed by the analysis of the reasons for the different penetration of these systems in the other countries.

Key words: *seismic isolation, energy dissipation, shock transmitters, shape memory alloys.*

1. Introduction

The conventional anti-seismic design of structures relies on their strength, namely on their capability of withstanding the effects of seismic vibrations (e.g., for buildings, increasing inertia forces from their base to their top and interstory drifts). Should such a design be adequate, it will save the structure from collapse even in a violent earthquake, but, also in this case, it cannot avoid damage to the structural elements and especially, the non-structural ones, including the building contents (i.e. human beings, in addition to objects). Nowadays, this sure damage is worldwide recognized to be quite a serious problem for all kinds of structures, but especially, as far as buildings are concerned, for the strategic and public ones: among the first, this is the case of hospitals, emergency management centers and all other structures which should remain fully functional (i.e. absolutely undamaged) during and after earthquakes, also in order to ensure an adequate emergency management; among the second, it is the case of schools and other highly populated buildings (Dolce et al, 2005).

In particular, schools, besides being commonly used in the post-earthquake emergency phase, are the public structures which host the most precious content of a community: its future! Thus, they need for a particularly high level of seismic protection, because even the collapse of partitions and other non-structural elements and the fall of objects may cause at least injuries. Moreover, internal damage may increase panic, which, in several cases, has caused even worse consequences than the structural damage itself. Finally, a high safety level of schools is quite important from the social and psychological points of view, as well: parents, in order to tranquilly live while their children are at school, far away from them, would need to be sure that they are fully safe there, that the school is better built than their homes (since this is frequently not the case in Italy, many children were not sent to school several days long after recent Italian earthquakes, even if moderate, like those of Marche and Umbria in 1997-98 and Molise in 2002).

However, also damage to normal dwelling buildings causes evident severe economic and social problems for the residents and the entire community: thus, this also should be minimized. In addition, with regard to the structure contents different from human beings, it is noted that, nowadays, even for non-strategic buildings they are frequently more valuable than the structure itself and quite vulnerable to seismic vibrations (let's think at computers, other sophisticated equipment, masterpieces, high tech products, etc.).

Last but not least, it has to be stressed that, in many countries (including Italy) a very large part of the existing buildings is not seismically safe, because earthquakes were not (at least properly) taken into account in their design or construction was inadequate. The problem is not limited to the masonry constructions (which are now considered as unsafe in rather seismic areas, if conventionally built, due to their absence of ductility), but also extends to several reinforced concrete (r.c.) buildings, even recent, which, unfortunately, show very poor quality. Moreover, earthquakes with unexpected violence recently occurred in many areas of the world, which have stressed the limits of the probabilistic seismological methodologies that are generally used to assess the seismic classification of the territory and have increased the seismic risk estimates for the conventional constructions.

2. Features and Principles of the Modern Anti-Seismic Techniques

Nowadays, the use of modern anti-seismic techniques, namely the seismic vibrations passive control (SVPC) techniques such as energy dissipation (ED) and, especially, seismic isolation (SI), is certainly the best way as to ensure a very high seismic safety level of constructions (Dolce et al, 2005). They fully protect not only the structural elements, but also the non-structural ones, including contents, and do this up to considerably higher earthquakes levels with respect to those tolerable by the conventional constructions. The SI systems are usually inserted at the structure base or better, nowadays, at a certain height in the first floor. In general, for civil structures, they are only horizontal and filter (thus, considerably decrease) the horizontal components of the soil seismic vibrations, which are the most dangerous when entering the structure. SI makes the structure laterally move practically as a rigid body and quite slowly (typically with periods of 2 s or more), although considerably (from 20÷40 cm in Italy to even 80 cm in California and Japan). This makes SI particularly adequate not only for the strategic constructions (which shall remain functional to quite violent earthquakes), but also for the highly populated ones, in particular schools: in fact, in addition to the capability of SI to ensure the absolute absence of damage (and, consequently, of victims and injuries), this absence of damage and the slow rigid movement of the school minimize panic (about schools, it shall be stressed that large spans are frequently present: this is a problem for the conventionally founded buildings, but not the seismically isolated ones).

Nowadays, the most commonly used SI devices are elastomeric (rubber) bearings (RBs), with a sufficiently large (at least 10%) damping coefficient so as to limit the lateral movement to a reasonable value (e.g. the high damping rubber bearings, HDRBs, or lead rubber bearings, LRBs), or without (low damping rubber bearings, LDRBs), but, in this case, coupled with dampers (see below). Recently, sliding devices (SDs), frequently in conjunction with RBs, also became common (SDs are very useful to support parts of the construction which sustain low loads). A steel-teflon re-centering sliding system that has been applied alone to some constructions, especially in the USA (or in countries where the USA are particularly influent) is the so-called Friction Pendulum System (FPS). In any case, re-centering is now correctly judged to be an essential feature of the SI systems (and this is excellently ensured by the RBs).

The ED devices (dampers) are usually inserted inside the structure between elements subjected to significant relative displacement; they “attract” and dissipate on themselves most of the seismic energy which, in their absence, would be dissipated by the entire structure through its damage and, for too violent earthquakes, collapse. There are several types of dampers: elastic-plastic (EPDs), viscous (VDs), visco-elastic (VEDs), friction-based (FDs), etc. It is evident that ED is somewhat less efficient than SI (dampers need for some structure deformation): however, this technique can be usually adopted when SI cannot be applied (e.g. for very flexible structures, quite soft soils and, especially, seismic retrofit of existing buildings where the necessary lateral gap neither exists nor can be created). In addition, the quite reduced structure distortions (and consequent very limited damage and absence of victims and injury) reduce panic, in this case also.

Besides SI and ED, further SVPC techniques have been developed and applied: among these there are the so-called shock transmitters (STs), which act as a fixed restraints during rapid vibrations (such as the seismic ones) while allow for free deformations during slow movements, and the shape memory alloy devices (SMADs), which are excellent load limiters, very suitable for the seismic upgrading of cultural heritage, thanks to their super-elastic and re-centering features.

3. BIRTH OF THE MODERN ANTI-SEISMIC TECHNIQUES

The SI concept is not new at all: it was known to the ancient Greeks and Chinese and maybe to Incas and was roughly applied by them (Dolce et al, 2005). However, the development of the modern reliable systems is rather recent and is due to that of rubber (Martelli et al, in press). After the erection of the Pestolazzi school at Skopje (Macedonia), isolated by means of poorly laminated LDRBs donated by Switzerland in the years 1960s (after the 1963 destructive earthquake), the French were the first who (at the beginning of the years 1970s) really recognized the great potential of SI for building protection: for them, the incentive was the need to develop advanced technologies for protecting their standardized nuclear plants and facilities (Pressurized Water Reactors – PWRs – and spent fuel storage pools) from earthquakes exceeding the design level (0.2 g peak ground acceleration – PGA) without being forced to modify the design. This led to the development of laminated synthetic neoprene bearings (NBs) and later, for the highest seismicity areas of French interest, of a system combining such bearings with superposed high friction (0.2) steel-brass SDs (called EdF system, because it was developed by Electricité de France). NBs and the EdF system were installed in those years not only on the aforesaid nuclear structures (the first in France, in the Cruas PWR and La Hague spent fuel storage pools, the second in the Koeberg PWR, in South Africa), but also on a certain number of French buildings and bridges: the first isolated French building, completed in 1977, was the 3-story high school at Lambesc, a small town that had been partially destroyed by the 1909 Provence earthquake; this SI application was followed in France by those to 20 further buildings (mainly 1-2 story houses), which were isolated in the years 1980s.

Roughly in parallel to the French, also the New Zealanders and Russians started developing SI systems and the first, later, ED devices, as well. In New Zealand the efforts were mainly devoted to the technology based on the use of lead (LRBs, etc.), while low cost inverted pendulum r.c. SI devices were developed for civil buildings in Russia, together with more sophisticated (and much more reliable) three-dimensional (3D) systems for the protection of military equipment from both seismic vibrations and (especially) those induced by nuclear explosions.

In 1975 the use of the SVPC techniques began also in Italy: the first application concerned the Somplago viaduct, where an ingenious SI system, formed by SDs and rubber bumpers was installed. This was also the first application of SI to bridges and viaducts in Europe, which was preceded, at worldwide level, by some of this kind only in New Zealand. One year later (1976), the aforesaid viaduct, which was located very close to the epicenter of the Friuli earthquake, performed very well in such an earthquake, contrary to the other conventionally erected bridges and viaducts in the epicentral area. This caused a quick extension of the use of the SVPC systems in such structures in Italy (it was the period when large efforts were being devoted there to the construction of the road and freeway system). As a consequence, Italy soon secured the worldwide leadership with regard to both the number (more than 150 at the beginning of the years 1990s) and importance of bridges and viaducts provided with SVPC systems.

In the first subsequent years, the Italian applications of the new systems remained limited to bridges and viaducts, for which ED devices were mainly used. However, the excellent experience that was being achieved through such applications and evidence of the actual bad behavior of conventionally constructed buildings in all Italian earthquakes, slowly started to produce interest, also in Italy, in the use of advanced technologies for the seismic protection of buildings, as well. This trend was evident mainly for strategic buildings (hospitals, fire stations, electrical facilities, city halls, etc.) erected after the 1980 strong Campano-Lucano earthquake: the Management Center of Naples is an example. This is the context where the first building application of both SI and ED systems took place in Italy, in 1981: in fact, it concerned the Headquarters building of the new Fire Station of Naples, which is located in the aforesaid Center. Shortly afterwards (in 1985), STs (besides SI and ED devices) were installed in a second building of the same Station, the so-called “Mobile Brigade”: this was the second Italian building application of the SVPC techniques and the first of STs. Both aforesaid applications allowed for not modifying the original buildings’ designs, which had been developed prior to the

Campano-Lucano earthquake, although the Naples area was seismically classified after this earthquake (it was considered as non-seismic before).

In 1985 the use of base SI also began in the USA (to the Foothill Communities Law & Justice Center at Rancho Cucamonga, California) and in Japan, while the first buildings provided with modern systems (HDRBs) in China and Chile were erected one at Shantou in 1991, and, respectively, one at Santiago in 1992 (twin isolated and fixed-base Andalucia Community buildings).

4. PRESENT APPLICATION OF THE MODERN ANTI-SEISMIC TECHNIQUES

In the years that followed the first aforesaid applications, the number of bridges and viaducts and buildings provided with SVPC systems increased continuously and more and more countries started using such systems (Chang et al, eds., 1989; Kuroda et al, eds., 1991; Martelli and Forni, eds., 1994; Saragoni Huerta, ed., 1996; Martelli and Forni, eds., 1998; Koh, ed., 2000; Martelli et al, eds., 2002; Melkumyan, ed., 2004; Dolce et al, 2005; Martelli et al, in press; Fujita, ed., to be published). Some further industrial plants (including a few high risk chemicals ones) have also already been protected with SI or ED systems and SI projects have been developed for all new nuclear plant types (in the near future the French will restart the application of SI, by isolating the Jules Horowitz Reactor for nuclear materials testing and the ITER plant for the study of controlled nuclear fusion, to be both built in their Cadarache Center). This extension of application of the SVPC systems has taken advantage of both detailed R&D studies (Martelli and Forni, eds., 2004) and (especially) the excellent behavior of a significant number of structures provided with them in violent earthquakes (see below).

Nowadays (October 2005) there are approximately 4500 constructions provided with SVPC systems in the world; nearly 4000 of these concern seismically isolated buildings. Some remarks on such applications, mostly taken from the book of Dolce et al (2005), are reported below, by stressing the use of SVPC devices manufactured in Italy, in Italy itself and abroad.

Applications in Japan

In Japan the number of building applications of the SVPC systems had a sudden increase (which never stopped afterwards) after the Great Hanshin-Awaji (or Hyogo-ken Nanbu) earthquake that struck Kobe on January 17, 1995, when the largest isolated construction in the world, the Ministry of Posts and Telecommunications (Fig. 1), and a second smaller isolated building of Mtsumura Gumi, both located a Sanda City, withstood the earthquake without any damage. They stood at about 30 km from the epicenter, namely at approximately the same epicentral distance as the USC Hospital and other isolated buildings at Los Angeles during the Northridge earthquake of exactly one year before, which had already shown a similar excellent behavior (see Sect. 4.4). The new Japanese building applications of SI alone were no less than 60 in the following eight months (against the previous overall 79) and more than 200 in each immediately subsequent year. In the last years approximately 100 large buildings were annually seismically isolated in Japan, to which a large number of private houses very recently added. This led the overall number of isolated Japanese buildings to at least 1700 in October 2003 and more than 2700 in June 2005. Many Japanese buildings have also been protected by ED systems of various kinds (for instance, those using buckling-restrained braces – BRBs –

were already around 250 in 2003) and application of SVPC systems to bridges and viaducts (which, in Japan, began later than that to buildings and has been largely based on SI) considerably extended, especially after the Kobe earthquake (after which SI was widely applied in Kobe itself, for both retrofit and reconstruction of the road and railway systems, and became obligatory there for overpasses and 2-storeys viaducts). Thanks to the numerous further confirmations of excellent behavior of isolated buildings during the three violent earthquakes that struck Japan in 2003-2004 (Miyagi-Oki, Off Tokachi and Mid Niigata – see Fig. 2) and on August 16, 2005, an even more rapid increase of applications is foreseen for the next years.

Fig. 1. Ministry of Post and Telecommunications at Sanda City, which withstood the 1994 Great Hanshin-Awaji earthquake without any damage, and details of a RB and an EPD of its SI system.

It is noted that, until 2001, also in Japan (similar to other countries – see below) it was necessary to submit the designs of isolated buildings to the approval a special commission. However, this always favored the technological development. Since when (in 2001, namely two years before Italy, see Sect. 4.5), according to the new seismic code enforced in 2000, the aforesaid submission is no more needed (with the exception of large buildings – but this also applies to the fixed-base conventional buildings), the exact evaluation of the number of Japanese isolated buildings has been obviously become impossible.

With regard to the ongoing or planned Japanese applications, those concerning high-rise buildings are particularly interesting. Until recently these were discouraged everywhere, because no SI system was capable, on the one hand, of increasing the SI period sufficiently above that of the fixed-base structure and, on the other hand, of withstanding the consequent large lateral deformations and uplift at the superstructure corners. In 2000, on the contrary, construction was completed at Tokyo for a 87.4 high (19,224 m2) building, supported by 30 LDRBs and 99 EPDs (Fig. 3); in addition, that of an even taller building, the “DT Tower” (130 m, 47,613 m2), isolated by means of a system formed by 12 linear ball devices, 6 LRBs and 6 VDs, was completed at Osaka in 2003. For these buildings, having a SI period of about 4 s, even tension stresses are allowed on the isolators (such stresses were prohibited by all codes until recently). This demonstrates the extreme reliability attained by the SI systems in Japan.

Furthermore, it is worthwhile citing the extraordinary application which is in progress at Sagamihara, in the Tokyo area: there, an enormous (12,349 m2) r.c. slab (artificial ground) was built, isolated at the top of the supporting columns, on which 21 dwelling buildings with 6 to 14 storeys are being erected (Fig. 4). This slab, below which a large parking was created, is supported by 48 LRBs (of 1200 mm diameters), 109 elastic sliders (of 400÷1200 mm diameters) and 85 “ball bearings” (BBs): they lead to a period of 6.7 s of the superstructure (111,600 t) and a design displacement of no less than 800 mm.

Besides the aforesaid large applications, to be stressed is the quite recent very rapid increase of the number of SI applications to Japanese private houses, even with small sizes and limited height (typically with two storeys). It occurred thanks to "liberalization" of the use of this technology. The most common system (in about 1300 cases) is formed by 2 SDs and 4 HDRBs. A second widely used system consists in special BBs coupled to VDs and adequately protected from water and dust. Each BB is formed by a steel sphere of about 130 mm diameter, surrounded by many much smaller steel spheres and supported by a 500 mm diameter steel plate, on which it rolls during the earthquake. The plate surface is hollow, to ensure re-centering. Since the SI period is independent of the mass for these systems, the latter are suitable for isolating even very light structures (e.g. wooden houses). The VDs may be locked through electromagnetic valves to provide the building with the necessary stiffness during violent wind storms.

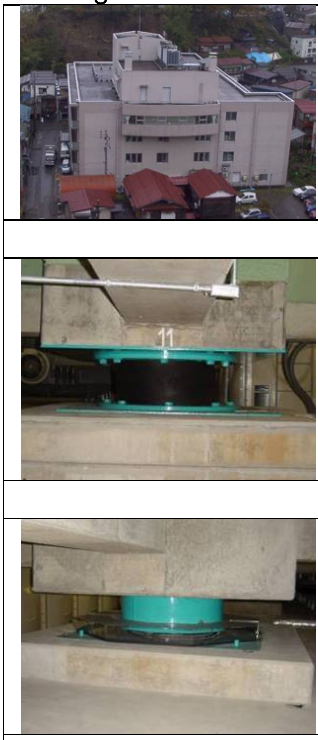

Fig. 2. R.c building at Ojiya City that withstood the 2004 Mid Niigata earthquake without any damage; its RBs & SDs.

Fig. 3. 87.4 high building, which was seismically isolated at Tokyo in 2000 (first Japanese application of SI to high-rise buildings).

Fig. 4. Sketch of the complex of twentyone 6- to 14-story buildings that are all being erected on a seismically isolated "artificial ground" at Sagamihara, in the Tokyo area.

Floor SI (FSI) is also going on in Japan, to protect, for instance, computers and air traffic control systems. The use of FSI had been initiated there in the years 1980s, before the beginning of base SI of entire buildings. Finally, as far of SI of industrial plants is concerned, detailed design studies were completed for the SI (even 3D) of all the different nuclear reactor kinds (seismically isolated nuclear plants may already be licensed in Japan, thanks to the recent availability of specific design codes); in addition, construction of the first Japanese isolated structure of nuclear interest (the "Nuclear Fuel Related Facility", protected by 32 LDRBs and lead dampers) was recently completed and applications are beginning in the high tech field (e.g. for a large factory for the production of semiconductors, which was isolated with LRBs, SDs and VDs in 2004).

Applications in Russia

The territory of Russian Federation includes areas that are among the most seismic worldwide. Destructive earthquakes occurred, for instance, in the Sakhalin island, in Kamchatka, Siberia and northern Caucasus. Recently, more modern and reliable applications, using HDRBs and steel-teflon SDs, added to the initial rough ones, performed in the years 1970s and cited in Sect. 3. The first retrofit with HDRBs concerned a bank at Irkutsk, an historical building which was seismically rehabilitated some years ago; this was recently followed by others, for instance a school in the Sakhalin island and the “State Concert Hall” at Grozny, in the Cechen Republic, and further projects were developed, in particular for cultural heritage (e.g. for the Kharlampiyevkaya church at Irkutsk and the National Drama Theater at Gorno-Altaisk, in Siberia). However, the progress of new applications is rather slow, due to the persisting economic crisis of Russia. Thus, the overall number of the Russian seismically isolated buildings, which was 500 in 2003, does not exceed 550 now.

Applications in the People Republic of China

In the P.R. China, where the beginning of application of the modern SVPC techniques had been considerably more recent (Sect. 3), the number of isolated buildings (dwelling buildings in several cases – see Fig. 5) reached 490 in June 2005 (270 being masonry buildings); in addition, there are already 25 buildings protected with ED systems and some isolated road and railway bridges and viaducts. SI is not applied only at the building base or at the top of the lowest floor, but also above an upper floor (for adding extra-storeys or erecting constructions with large asymmetries along their height), or at top of the building (to support, in case of retrofit, one or two additional floors acting as Tuned Mass Damper – TMD), or on structures connecting adjacent buildings characterized by different vibrational features. Nowadays, application is rapidly progressing, in spite of a rather severe code (although less penalizing than the US one, see Sect. 4.4) and continuing need for submitting the designs for approval to a special commission.

Fig. 5. Dwelling building at Shantou and one of its HDRBs (first Chinese application of modern SVPC systems in 1991), which withstood a significant earthquake without any damage in 1994 (left and center); complex of 60 new masonry dwelling buildings isolated with HDRBs in Western China in 1996 (right).

Fig. 6. Mock-up the “Isolation House Building on Subway Hub”, under construction close to the Peking center, which was tested on shake table, and picture of the entire complex.

To be cited is the “Isolation House Building on Subway Hub”, located close to the Peking center (Fig. 6), which is now the largest application of SI worldwide. It consists in the construction (which was nearly completed in June 2005) of fifty 7- to 9-story base isolated buildings, with a total floor area of 480,000 m2. The peculiarity of this project is that all buildings have been isolated above a unique enormous 2-story substructure of 3 km2 (1500 m x 2000 m), which contains all facilities and infrastructures, including trains and underground. The objective has been to optimize the use of a wide very valuable central area, which was previously occupied by train lines and the underground, by minimizing the consequent vibrations and noise. For this quite important application SI allowed for a 25% saving of construction costs: thanks to this it was possible to fund the rising of the 50 building by 3 storeys in average, with a 100,000 m2 increase of the total floor area.

Applications in the USA

In the USA, contrary to Japan and P.R. China, the growth of building application of SI was very slow in the last years. This occurred in spite of the excellent behavior of all three Los Angeles isolated buildings that were located close (at 30 km) to the epicenter of the Northridge earthquake of January 17, 1994: the Fire Command at Control Facility (although it was locally damaged due to construction and subsequent repair errors of the entrance gangway, which locally obstructed the free motion of the isolated superstructure and, thus, also caused some local amplification of the input vibrations), the Emergency Operations Center (which was still under construction), and, especially, the University of Southern California (USC) Hospital (Fig. 7). The first (using HDRBs) and the third (provided with LRBs) had been completed in 1990 and 1991, respectively, while the second (supported again by HDRB) was opened to activity in 1994, after the earthquake.

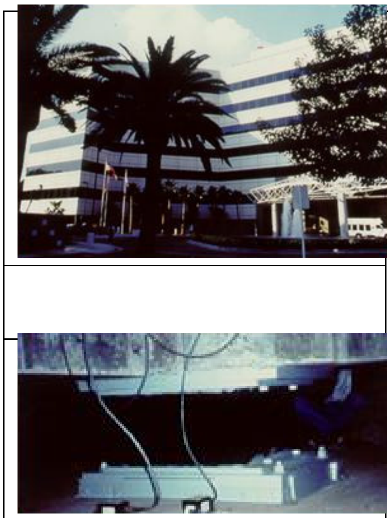

Fig. 7. The new USC Hospital at Los Angeles, completed in 1991, which remained undamaged and fully functional in the 1994 Northridge earthquake, and one of its LRBs.

Fig. 8. San Francisco City Hall, built in 1912 and damaged by the 1989 Loma Prieta earthquake, for which retrofit with 530 LRBs and 62 SDs was completed in 2000.

Fig. 9. The new 911 Emergency Communications Center at San Francisco, protected by HDRBs to remain fully functional to 8.3 magnitude quakes (construction was performed in the years 1990s).

The reason for the aforesaid difficult extension of building application of SI in the USA is similar to that which, from the end of 1998 to the beginning of May 2003, had hindered the penetration of the SVPC techniques in Italy (Sect. 4.5), namely a particularly penalizing code for isolated buildings (curiously, different from the case of the US isolated bridges and viaducts). Such a code does not allow for taking advantage of the benefits of SI (e.g. the quasi-rigid motion of the superstructure) and practically always imposes, at least in California, the adoption of near-field conditions, with a consequent 15% increase of the seismic input. Thus, the US isolated buildings remain “only” approximately 100 and are mostly public. However, they are frequently huge constructions and 45% of them are retrofits.

The U.S. isolated buildings are mainly located in California, but there are applications also in other states, such as Utah, Oregon, Washington, Nevada and Tennessee (see Martelli and Forni, eds., 1998, Koh, ed., 2000, and Martelli et al, eds., 2002). Important new isolated constructions concern, in addition to those mentioned in Sect. 3 and above:

- further civil defense, management and control public buildings (e.g. 911 Emergency Communications Center at San Francisco, Emergency Communications Center at San Diego, Washington State Emergency Operations Center at Camp Murray, Long Beach Emergency Services Center, Public Safety Building at Berkeley, Water Quality Laboratory at Portland, Traffic Management Center at Kearny Mesa, AutoZone Headquarters at Memphis);
- further medical buildings (e.g. M.L. King, Jr. - C.R. Drew Diagnostics Trauma Center at Willowbook, LAC + USC Medical Center at East Los Angeles, San Bernardino Medical Center at Colton);

- city halls (e.g. Hayward City Hall);
- religious buildings (e.g. Cathedral of Our Lady of the Angels at Los Angeles);
- other public civil structures (e.g. San Francisco Public Library, San Francisco Airport at San Bruno);
- industrial, bank and military buildings (e.g. Aircraft Simulator Test Facility at Salt Lake City, Kaiser Regional Data Center at Corona, Pixar Center at Emeryville, Insurance Company Data Center near Seattle, Titan Solid Rocket Motor Storage at the Vandenburg Air Force Base, Microchip Fabrication Facility at Newport Beach).

In addition, important retrofits performed in the USA with SI were to:

- city halls (e.g. Salt Lake City and County Building, Oakland, San Francisco and Los Angeles City Halls, Berkeley Civic Center);
- medical buildings (e.g. Long Beach Hospital, Hoag Memorial Hospital Nursing Tower at Newport Beach, California);
- school buildings (Kerkhoff Hall of the University of California at Los Angeles, Mackay School of Mines at Reno);
- cultural heritage buildings (e.g. Asian Art Museum at San Francisco, Hearst Mining Memorial Building at Berkeley);
- other public civil structures (e.g. State of California Justice Building and U.S. Court of Appeals at San Francisco, Campbell Hall at Monmouth, Hughes Buildings, S-12, at El Segundo, Channing House Retirement Home at Palo Alto);
- industrial buildings and structures (e.g. Rockwell International Corporation Headquarters at Seal Beach, Seattle Standpipe & Water Tank at Seattle).

The SI systems used in the aforesaid applications have been HDRBs and LRBs (sometimes in conjunction with LDRBs and, in a few cases, with SDs, VDs and other damper kinds), as well as, since recently, FPS. That to the Salt Lake City and County Building was the first U.S. retrofit with SI, performed in 1989, after an earthquake had severely damaged it. Of note is also that several Californian existing buildings, such as, for instance, the City Halls of San Francisco (Fig. 8), Oakland and Los Angeles, were seismically rehabilitated to withstand seismic events with magnitude larger than 8 (the first two had been damaged by the 1989 Loma Prieta earthquake) and that the new Californian emergency management centers, e.g. that of San Francisco, were designed to remain operational to even larger magnitude earthquakes (Fig. 9).

Due to the high SI costs in the USA, very few applications concern dwelling buildings: among these we cite an apartment building at Marina of San Francisco, the foundations of which had been broken by the 1989 Loma Prieta earthquake (it was retrofitted with FPS in 1991) and two new residences at West Los Angeles, which were protected by 3D devices in 1992 (the latter, however, suffered some damage during the 1994 Northridge earthquake, due to rocking effects of vertical SI).

Contrary to SI, the use of ED systems in the US buildings is progressing satisfactorily, because it is regulated by a more reasonable code. Initially, the most commonly used dampers in the USA were VDs (there were already approximately 40 buildings protected by them in 2001), although other devices were also adopted, such as EPDs (e.g. to the Wells Fargo Bank at San Francisco), VEDs (e.g. to a 13-story steel frame building at San

Jose, California) and, especially, FDs manufactured in Canada (with 12 of the 63 applications of this systems in 2001, for instance to the retrofits of a 10-story r.c. building at Pasadena, California, and an assembly building of the Boeing Commercial Aircraft factory at Everett, Washington, as well as to the new Moscone Center Expansion Project). In 2000, the use of BRBs also began in the USA: in 2003, there were already 30 U.S. buildings protected by such a system, completed or in progress.

Finally, with regard to the applications of SI to bridges and viaducts, the first two were performed in 1986 for retrofitting the Santa Ana River bridge and Sierra Point Overhead (the latter remained undamaged during the 1989 Loma Prieta earthquake). The number of new and retrofitted buildings that were protected by SI was over 40 in 1994 (Martelli and Forni, eds., 1994), then went on increasing and ED devices and STs also began to be used. Some of the latter have been manufactured in Italy.

Applications in Italy

The Italian activities concerning development and application of the SVPC systems are being performed taking advantage of the collaborations established in the framework of the Italian Working Group on Seismic Isolation ("Gruppo di Lavoro Isolamento Sismico" – GLIS) at national level and of the Anti-Seismic Systems International Society (ASSISi) at international level. GLIS was founded in 1989 and has now over 290 members, representing all the parties interested in the development and application of the SVPC techniques, including both engineering and seismological aspects (universities, research centers, design offices, manufacturing companies, building companies, national, regional and local Institutions, etc.); most Italian designers of buildings provided with SVPC systems are GLIS members. ASSISi was founded in 2002 and has now 102 individual members (engineers and seismologists) and 7 corporate members, representing 29 countries and the European Commission (EC). Since 2004 GLIS has been an ASSISi corporate member; in 2005 it promoted the foundation of the Italian Territorial Section of the Society.

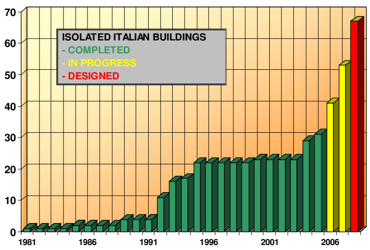

Fig. 10. Total number of Italian seismically isolated buildings during years.

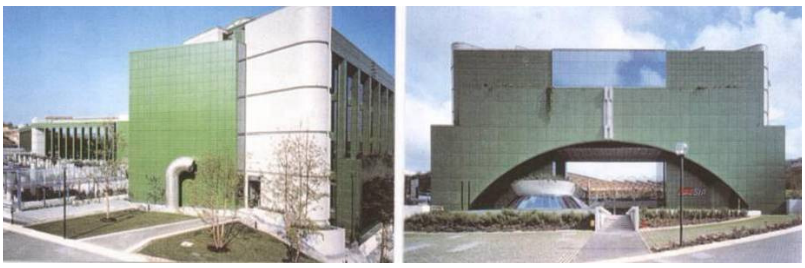

Fig. 11a. Regional Center of Telecom Italia at Ancona, after its completion with 297 HDRBs in 1992 ("rectangular" shape buildings and entrance arch building).

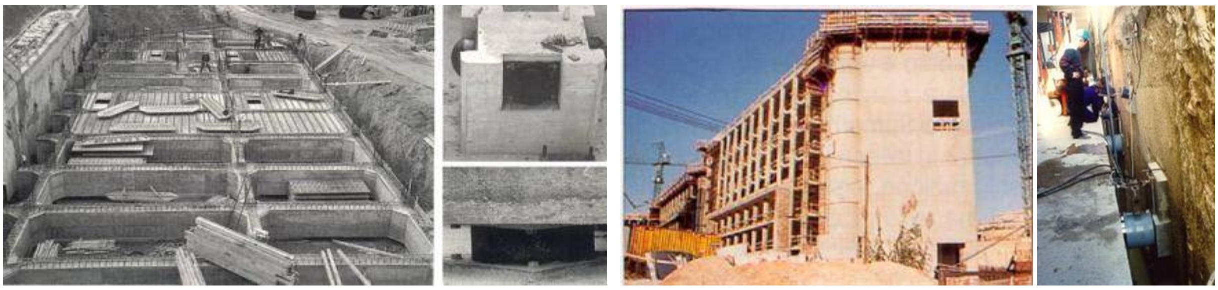

Fig. 11b. Foundations of a Telecom Italia building at Ancona (left); one of its HDRBs (right, below) and a fail-safe bumper (right, above).

Fig. 11c. The Ancona Telecom Italia building subjected to on-site test in 1990 (left) and view of the hydraulic jacks used for pull-back tests (right).

The first Italian applications of SVPC systems were possible because the national seismic code that regulated constructions in seismic areas until May 8, 2003 (Law Nr. 64) formally did not exclude the use of such systems (although it was not intended to consider the structures provided with them as conventional). Some remarks on the progress of the application of SVPC systems to Italian bridges and viaducts have already been provided in Sect. 3. As regards buildings, those provided with SI systems alone were already approximately 20 at the beginning of the years 1990s (see Fig. 10). In 1990 the dynamic on-site tests performed on one of the five isolated buildings (8 storeys, 25 m height) of the present Marche Regional Centre of Telecom Italia (which is the first large Italian application of SI) had a large worldwide echo: this building (Fig. 11), supported by HDRBs (like the other four of the Center and most subsequent Italian building applications of SI) was subjected to both forced vibration and pull-back tests, the latter with lateral displacements of up to 110 mm (i.e. 80% of the design displacement), and was analyzed in detail by means of sophisticated numerical methods.

At the beginning of the years 1990s, thanks to the aforesaid and other applications, everybody was confident in Italy that the use of SI was destined there to a rapid extension. In fact, the possibility of largely increasing building seismic protection through these systems, easily applicable and leading to limited additional costs (if any), was judged to be extremely attractive (SI had allowed for 7% saving of construction costs for the Ancona Telecom Italia Center, partly due to simplification of the foundations and feasibility of asymmetric superstructures). However, shortly after the on-site tests on the building of Fig. 11c, SI suffered a sudden and unexpected stop. In fact, the Ministry of Constructions judged the Telecom Italia buildings not to be in conformity with Law Nr. 64 and, thus, that their design had to be submitted for approval to its “High Council of Public Constructions”. An endless bureaucratic process began, which could be concluded only in 1992, thanks to the buildings structural safety certification that was signed by the author of this paper. This certification was possible because Law Nr. 64 was not infringed from the formal point of view and because, as far as the substantial aspects are concerned, the structure safety had been widely checked thanks to the previously mentioned numerical and experimental studies. However, although the Ancona Telecom Italia application was saved in this way, its misfortunes immediately caused a nearly complete stop of the use of SI in Italy (see Fig. 10).

In spite of a proposal for design guidelines for isolated structures prepared in 1993 by a task-force of experts led by the National Seismic Survey (SSN), this situation went on to the end of 1998, when, at last, the Ministry of Constructions published its guidelines. In the meantime, the 1997-98 Marche and Umbria earthquake (magnitude M = 6.0, according to the United States Geological Survey) had also helped to renew the interest in the SVPC techniques, also in Italy. Although, contrary to the SSN guidelines, those of the Ministry were rather penalizing for the erection of structures provided with SVPC systems (in particular, SI), there was again sufficient confidence in Italy to be quickly able to recover the lost time with respect to other countries. Unfortunately, the bureaucratic process which was necessary to obtain the Ministry approval of SI designs proved to be extremely complicated, uncertain and time-consuming, by considerably (and, in may cases, unacceptably) protracting the structure completion time. This began discouraging the use of the SVPC systems again.

However, at last, on May 8, 2003, a very advanced new seismic code was enforced in Italy, together with the seismic reclassification of the national territory, thanks to Ordinance 3274/2003 of the Prime Minister. This Ordinance was partly a consequence of the large echo provoked by the tragedy of the village of San Giuliano di Puglia (Campobasso), where 27 children (including all the youngest, those born in 1996) and a teacher were killed by the collapse of their very badly built primary school (Fig. 12) during the moderate Molise earthquake of October 31, 2002 (M = 5.9). The new seismic classification extended the percentage of the Italian territory considered as seismic from 43% to 70% of the entire land, increased the seismic levels for several already seismically classified areas and suggested minimum seismic design requirements also for the so-called “non-seismic” areas (no significant earthquakes were known in the area of San Giuliano di Puglia in the previous 1000 years): all this stresses the problem of may existing buildings which are now located in seismic areas, but were not designed according to any anti-seismic requirements.

Like Eurocode 8 (EC8), the new Italian code, which was developed taking advantage of the excellent R&D work performed in Italy since the middle of the years 1980s, contains two chapters devoted to SI of buildings and bridges and viaducts, respectively. It is consistent with EC8, but several additional aspects are dealt with, to permit an easy design of strongly non-linear SI systems. Though not directly addressed in a specific chapter, also the use of the ED strategy is permitted, according to the general criteria and design analysis methods. Consequently, the application of SVPC systems does not require the approval of the “High Council of Public Constructions” any more and the designers are encouraged to apply such systems. In particular, as far as SI is concerned, the new Italian code is much less penalizing than the U.S. one, because it correctly allows to take advantage of the benefits of SI in largely reducing the seismic vibrations and forces, inducing a quasi-rigid motion of the superstructure and making the erection possible for even quite asymmetric buildings (through an appropriate design of the SI system to minimize torsion effects). The consequence is that, for at least significantly seismic areas, the SI implementation costs are now frequently balanced in Italy by the reduction of construction costs of the superstructure and foundations (for highly seismic areas SI may also lead to savings).

Fig. 12. Views of San Giuliano di Puglia before the 2002 Molise earthquake, as damaged by this earthquake and during and after the demolitions of the debris of the collapsed school and other buildings; view of the site for the erection of the new school (which will be seismically isolated by means of 61 HDRBs and 13 SDs, based on a design coordinated by ENEA) and sketch of the designed construction.

Nowadays, two years after the enforcement of the new code, one can be really optimistic in Italy. In fact, this country has all the necessary knowledge and expertise, including the European leadership on R&D for all application fields. This confidence has already been confirmed by the importance of some recent remarkable applications, completed in the last two years or in progress, and by the numerous new designs (Fig. 11). These applications and designs (which will lead the number of the Italian isolated buildings to certainly over 80 in a few years) concern all civil structure kinds: bridges and viaducts, strategic and public buildings (schools, civic centers, emergency management centers, hospitals, airport buildings, churches, hotels, etc.), dwelling buildings and cultural heritage. In addition, based on the quite promising results of recent R&D projects, there is a great potential of application of the SVPC systems to the industrial plants, as well, in particular the high risk chemical ones. The increasing installation of Italian SVPC devices also in other countries is a confirmation of Italy's leading role in this field, at least at European level (see the next Sections).

Recent Italian application to strategic and public buildings

For schools to be cited is the recent installation of: several EPDs in various seismic upgradings (e.g. La Vista, Giacomo Leopardi and Via Lazio schools at Potenza, A. Mileo school at Latornico, Polytechnical of Marche at Ancona, see Fig. 13); HDRBs and SDs for the new school of San Giuliano di Puglia (Fig. 12); LRBs and SDs for that under construction at Bojano (Campobasso); various SI devices (including HDRBs) for the five new ones to be erected in Tuscany (to replace unsafe existing constructions) and for that of Marzabotto (Bologna); a SI system to be defined (and maybe other SVPC devices) for the rehabilitation of the large (1500 students) quite unsafe Romita high school buildings at Campobasso (Fig. 14) and a school at Rieti (the projects concerning the schools at San Giuliano di Puglia, Marzabotto, Campobasso and in Tuscany have been developed within collaborations with ENEA and, for the latter, GLIS).

Fig. 13. “Giacomo Leopardi” school at Potenza after its retrofit by means of steel bracings provided with EPDs, similar to the “La Vista” and “Domiziano Viola” schools.

Fig. 14. Romita high school at Campobasso to be retrofitted with SI and maybe other SVPC systems (first retrofit of Italian schools using such systems).

Fig. 15. The isolated fire station (52 HDRBs and 5 SDs), which was recently completed at the Civil Defense Center at Foligno.

For emergency management centers the following systems have been or will be used: HDRBs, SDs and maybe other SVPC devices in the erection of the 13 buildings of the new Civil Defense Centre of Foligno (Perugia), one already completed (Fig. 15) and two under construction with a similar SI system (collaboration has been provided by ENEA to the Umbria Regional government for the review of the designs); again HDRBs and SDs for a Civil Defense building (Red Cross headquarters and Civic Room) that is being erected at Gaggio Montano (Bologna).

For hospitals recently adopted systems have been: HDRBs in the new hospitals that are under construction at Udine (Fig. 16) and Frosinone and in an already completed new helicopter surface of the Varese hospital; STs in the new hospital being erected at Mirano (those at Udine and Mirano are the first Italian hospitals protected by SI devices and STs, respectively).

For other public buildings recent application concerned: VDs for the new church “Dives in Misericordia” at Rome (Fig. 17); HDRBs for the seismic upgrading, with cut of the supporting columns and walls, of the Rione Traiano Civic Center at Naples (left incomplete before the 1980 Campano-Lucano earthquake, after which Naples was seismically classified – see Fig. 18); STs to three new high-rise buildings of the Emilia-Romagna Regional government at Bologna and for the seismic retrofit of the Malpensa airport; a SI system formed by VDs and SDs for the new headquarters of the association “Fratellanza Popolare – Croce d’Oro” under construction at Grassina, near Florence (first Italian application of this SI system kind, the certification of which has been entrusted to the author of this paper); SDs to support the ceiling of the new hall of Crown Plaza Hotel at Caserta on three of the four existing buildings connected by such a structure.

Fig. 16. The new seismically isolated wing of Gervasutta Hospital at Udine, during construction (2005) and view of some of its 52 HDRBs.

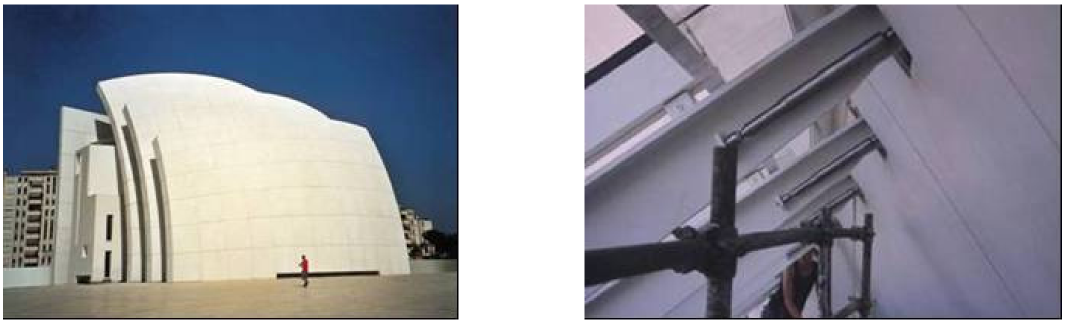

Fig. 17. The new “Dives in Misericordia” Church at Rome and some of its 32 VDs (2004 – first Italian application of SVPC systems to new churches).

Fig. 18. Views of the Rione Traiano Civic Center at Naples after the structure completion in the years 1970s, of its foundation columns and walls cut during upgrading with approximately 630 HDRBs, of the new steel reinforcing floor installed above the isolators and of the upgraded building in 2004 (first retrofit with SI in the European Union – EU).

Recent Italian application to dwelling buildings

In the field of dwelling buildings, which is strategically quite important because of the large size of its potential market, Italy is certainly able to soon widely extend the adoption of the SVPC systems, to both new and existing constructions. This is demonstrated by the recent or ongoing applications. In particular, seismic rehabilitation with SI concerns two r.c. buildings, completed at Solarino (Syracuse) in 2004 (first EU building application of SDs in conjunction with HDRBs) and the r.c. building of Fig. 19, which is in advanced progress at Fabriano (Ancona) with HDRBs (first EU building application of SI with sub-foundation, the safety certification of which has been entrusted again to author of this paper).

Moreover, application of SI to new constructions is in progress for the erection of four new r.c. buildings at Cerignola (Foggia), protected by HDRBs (Fig. 20), in the framework of the so called “Quarters Contracts I” Program, funded by the Ministry of Constructions for the rehabilitation of degraded areas (first Italian application designed according to the new code – also in this case the safety certification of which was entrusted to the author of this paper), a new r.c. building at Santa Severina (with HDRBs and SDs), at least two r.c. buildings at San Giuliano di Puglia (with HDRBs) and two masonry buildings at Corciano (Perugia) (the first EU application of SI to masonry buildings).

Fig. 19. Damage of the 1997-98 Marche and Umbria earthquake to the Fabriano house and new underground floor after the insertion of 56 HDRBs and cut of most old foundation piles (April 2005).

Fig. 20. Seismically isolated buildings under construction at Cerignola (in June 2005 on the left and in September 2005 at the center) and view of two of the 124 HDRBs installed at the top of their first floor.

Further planned applications of SI to dwelling constructions concern: the retrofit of the fixed-base design of five r.c. buildings at Rome (Ponte di Nona), which had been developed when Rome was not seismically classified; the retrofit of a masonry buildings near Belluno, being developed with the collaboration of ENEA (this will be the first EU application of SI for the seismic rehabilitation of masonry constructions); the recently decided construction of twelve new r.c. isolated buildings at Lamezia Terme (Catanzaro); reconstruction (as decided by the Marche Region, based of a design developed by ENEA) of at least one set of houses at Mevale di Visso (Macerata) with the original masonry materials and construction methods on a platform supported by HDRBs (this village was fully destroyed by the 1997-98 Marche and Umbria earthquake). Finally, new applications of SI and ED systems have also been planned within some projects that were recently approved by the Ministry of Constructions in the framework of the “Quarters Contracts II” Program (e.g. those developed by the municipalities of Acireale and Modica in Sicily, Ariano Irpino in Capania, Torremaggiore and Ruvo di Puglia in Puglia, etc.).

It is worthwhile stressing that the field of masonry constructions, in which the application of SI is now beginning in Italy, is particularly interesting, because this technique opens the possibility of wide applications to such constructions even in very seismic areas; on the other hand, this possibility has already been well understood in other countries, like, for instance, the P.R. China (see Sect. 4.3).

Recent Italian application to cultural heritage

In the field of the seismic protection of cultural heritage by means of SVPC systems, Italy is really the worldwide leader. With regard to buildings, important seismic upgrading interventions have already been completed, using various SVPC systems. More precisely, to limit ourselves to the most recent applications (i.e. those performed after 1998), SMADs were used to restore: the Upper Basilica of St. Francis at Assisi, severely damaged by the Marche and Umbria 1997 earthquake, to connect the tympana to the transept roof (Fig. 21); the bell tower of the Church of St. Giorgio in Trignano (Reggio Emilia), severely damaged by the 1996 Reggio Emilia and Modena earthquake (this retrofit was performed with the collaboration of ENEA); the Cathedral of St. Feliciano at Foligno (Perugia) and the Church of St. Serafino at Montegranaro (Ascoli Piceno), which had also been damaged by the 1997-98 Marche and Umbria earthquake; the Church of St. Pietro in Feletto (Treviso), again damaged by an earthquake; the Badia Fiorentina at Florence.

Moreover, similar to some previous applications (Martelli et al, eds., 2002), STs were used the strengthen the Upper Basilica of St. Francis at Assisi (Fig. 21) and are now being adopted in the restoration of the MAXXI museum at Rome. The only so far existing application of ED devices to cultural heritage structures (due to the usual larger invasiveness) concerns the Cathedral of Santa Maria di Collemaggio at L'Aquila, where they were installed to strengthen the roof. To be reminded are also the pilot applications with sub-foundation that have been planned for the two churches of St. Giovanni Battista at Apagni (Sellano, Perugia) and Santa Croce at Case Basse (Nocera Umbra, Perugia), which had also been both severely damaged by the 1997-98 Marche and Umbria earthquake: their conventional restoration was completed and their retrofit by means of SI and sub-foundation (which was judged compatible with the conservation requirements) was designed by ENEA and other partners and submitted to the approval of the Superintendence for Cultural Heritage of Umbria Region for funding (the installation of HDRBs is foreseen for both churches, in conjunction with SDs for the first).

Fig. 21. The Upper Basilica of St. Francis at Assisi – From left to right: after its restoration; tympanum damaged by the first shock of the 1997 earthquake; during and after the installation of 47 SMADs between both tympana and the transept; during installation of the 34 STs.

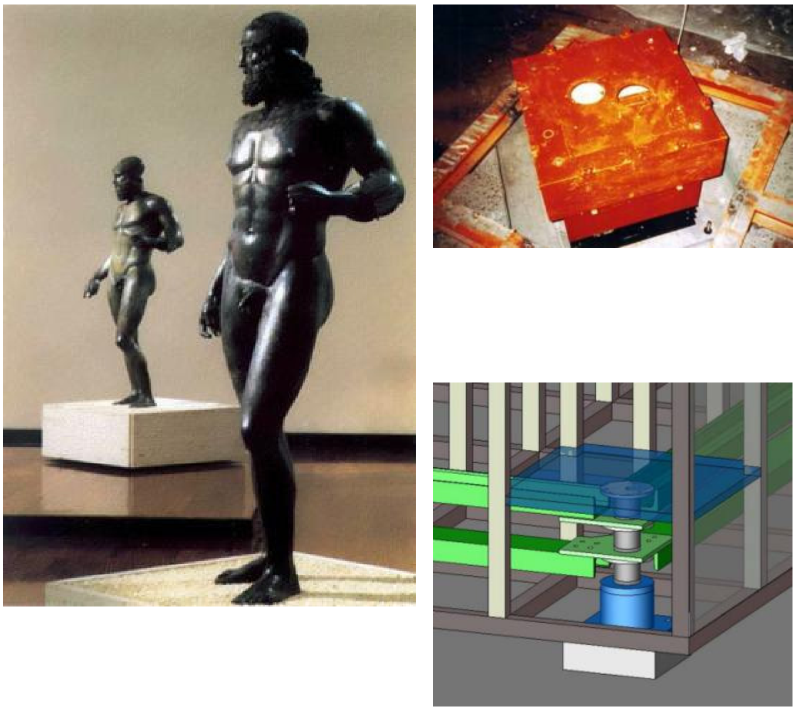

Fig. 22. Bronzes of Riace (Reggio Calabria Museum) and their three-stage system of 4 HDRBs per stage (which was also used to protect the bronze statue of Germanicus emperor at the Perugia National Museum and the Satyr of Mazara del Vallo).

Fig. 23. David of Michelangelo, to be provided with an innovative seismic protection system.

SVPC systems have also already been installed in Italy for protecting single masterpieces, some of which being very precious. In particular, three-stage HDRB systems were installed to protect, for instance, the Bronzes of Riace at the Museum of Reggio Calabria (Fig. 22), as well as the bronze statue of the Germanicus Emperor at the National Museum of Perugia and that of the Satyr of Mazara del Vallo: such systems allow for overcoming the instability problems that would occur using the usual one-stage systems because of the limited weight of the bronze statues (this entails small HDRB diameters to get the necessarily low horizontal stiffness of the SI system, while the HDRB height is imposed by the horizontal design displacement). A different quite innovative system, formed by steel-teflon SDs in parallel with SMADs (which provide both ED and re-centering), was used to protect the statues of Scylla and Neptune at the Museum of Messina. Finally, a special SI system formed by four 3D isolators was developed and manufactured by ENEA and other partners for protecting the very fragile Roman ship excavated at Ercolano (Naples), after its long burial under the materials erupted by the Vesuvius volcano in 79 A.D., and is ready to be installed in the local Museum: each device consists in a spring with a VD for vertical SI and damping and three steel spheres rolling on a steel plate, with a re-centering rubber cylinder, for horizontal SI (due to the limited height, there are no rocking problems).

It is worthwhile stressing that the field of cultural heritage is particularly important in Italy, because this country owns quite a large of it. Application of the SVPC systems in this field still requires considerable R&D activity: in fact, for the seismic upgrading of the related buildings, in agreement with the conservation requirements, it is first necessary to develop and apply low invasiveness systems, which shall be reversible and, especially, compatible with the original structure; secondly, each cultural heritage structure has specific features and, finally, many of such structures are frequently not well known. Several further masterpieces, in addition to those previously mentioned, may be adequately protected from earthquake damage in Italy. The first (and best) way is to build seismically isolated museums to host them, or to retrofit the existing museums using SI (an example is the planned rehabilitation of the Iran Bastan Museum at Tehran, see Sect. 4.12 and Fig. 33). An alternative possibility is the use of different SVPC systems to protect new or existing museums (the already mentioned MAXXI Museum at Rome is the first Italian application of this kind). The third approach, that of isolating the single masterpieces, should be adopted only if the latter are located in conventionally built museums where, however, no even partial collapses may occur, or if they are adequately protected against collapses of the surrounding structures. In any case, even for the worldwide famous David of Michelangelo (Fig. 23) studies are already in progress, in the framework of a collaboration involving ENEA, for developing a suitable seismic protection system: in fact, this heavy (57 kN) and tall (4.8 m) masterpiece, which is hosted by the "Galleria dell'Accademia" at Florence, has quite seriously fissured ankles and a very peculiar mass distribution, which now make it unable to withstand even the moderate earthquakes (0.15 g) which have a significant probability of occurrence in the Florence area.

Applications in Taiwan

Contrary to previously mentioned countries, Taiwan became particularly active in the application of the SVPC systems only very recently, after the destructive 1999 Chi-Chi earthquake and the consequent revision of the national seismic design code, which introduced the possibility of using the aforesaid systems without any particular difficulty. In December 2004 the number of seismically isolated buildings was already 24 and 87 further new or existing buildings had been protected by ED devices. Furthermore, approximately 20 bridges and viaducts had been isolated by means of LRBs or HDRBs. In numerous cases devices manufactured in Italy have been used. Among the ongoing applications it is worthwhile citing the Taipei Financial Centre, a 509 m high skyscraper, the vibrational motion of which (in particular, that caused by winds) is controlled by an enormous TMD provided by 8 VDs manufactured in Italy.

Applications in Armenia

The territory of Armenia is also particularly seismic (the last extremely violent event was the 1988 Spitak earthquake). In spite of still being a developing country, with a very limited population, Armenia has been very active in the SI field since 1994. At present 19 isolated buildings have already been completed and 2 more should be ready within 2005. The most recent buildings are high-rise ones (to 17 storeys). They are both dwelling and public, r.c. and (in some cases) masonry, buildings. The latter include a school, a clinic and multifunctional complexes. Three retrofits using SI have already been performed: the first was in 1996 (namely well before the Italian ones), while the last one was in 2002 and concerned a masonry school (Fig. 24). In all Armenian SI applications locally manufactured HDRBs are used. These devices are also exported, for instance to Syria, for SI of bridges and viaducts.

Fig. 24. The masonry school nr. 4 at Vanadzdor (Armenia), which was seismically retrofitted with HDRBs in 2002; provisional support of the entrance columns during works; opening of the foundations to insert the new r.c. columns and HDRBs; one HDRB already inserted in the new r.c. column, before the full demolition of the old walls at the beams' positions and casting such beams.

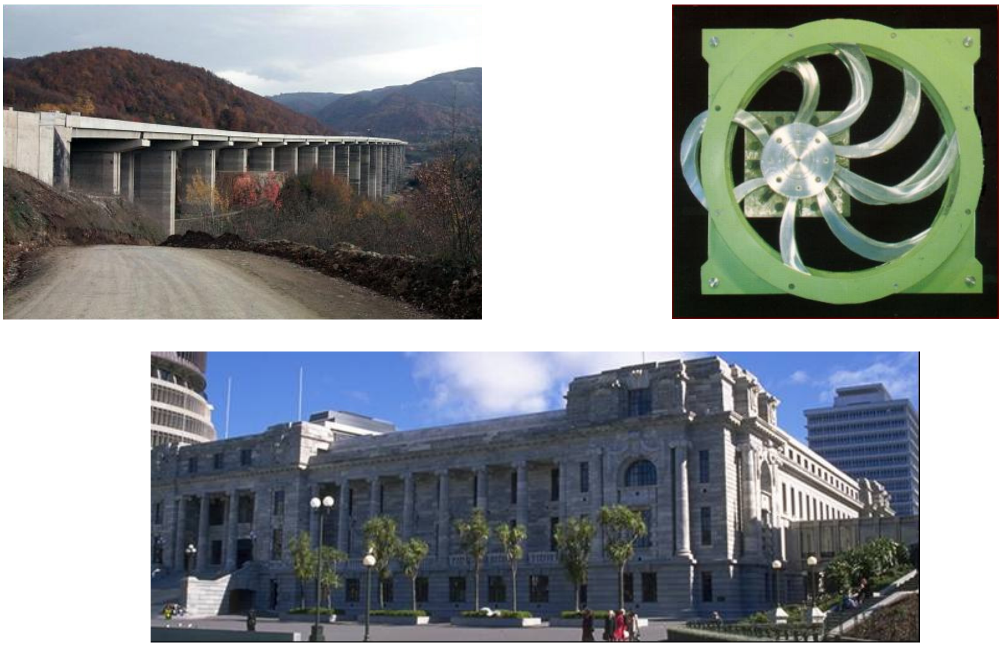

Fig. 25. The New Zealand Parliament at Wellington built in 1921 and seismically retrofitted with LRBs in 1992-93.

Applications in New Zealand

New Zealand is a high seismic hazard country which is even less populated than Armenia, but certainly much more developed. We have already mentioned in Sect. 3 that this country was the "cradle" of the SVPC techniques, even more than France. Many kinds of SVPC system concepts developed in New Zealand (in particular, the LRBs and other lead-based devices) were "exported" to other countries (especially to Japan and the USA). In August 2005, in addition to the numerous applications to bridges and viaducts, there were already 11 isolated buildings. The first was erected in 1987. Three applications are retrofits: the first, which was performed using LRBs in 1992-93, concerned the Wellington Parliament, a 5-story historical building erected in 1921 (Fig. 25). In New Zealand SI has been considered fully reliable for the protection of both new and existing constructions for a long time. The preferred system remains that using LRBs, which are frequently installed together with SDs: in fact, a large new hospital isolated by means of 135 LRBs e 135 SDs is now being erected at Wellington.

Applications in Turkey

The only application of SVPC systems which existed in Turkey before the 7.6 magnitude earthquake of Kocaeli of August 17, 1999 was that of EPDs (manufactured in Italy) to the Bolu viaduct of the Istanbul-Ankara freeway. During such an earthquake, the new terminal of the Ataturk international airport at Istanbul, which was being completed, was damaged and it was decided to seismically retrofit it at the roof beams level (base SI was judged too costly, due to the advanced construction stage). This intervention, performed using the FPS, caused the beginning of SI application in Turkey. Subsequent applications also already include: the retrofit (by means of FPS) of the aforementioned Bolu viaduct (Fig. 26), where the previously existing EPDs, although they had saved the structure from collapsing, had been destroyed by the second 1999 Turkish earthquake, the 7.2 magnitude Duzce shock of November 12 (its PGA had been approximately three times larger than the EPD design value and had even fractured the ground across the viaduct); two large cylindrical Liquefied Natural Gas (LNG) tanks at the Aliaga-Izmir Terminal of Egegaz (Fig. 27), the safety of which is thus ensured to a 0.7 g horizontal PGA earthquake; the construction of the new university hospital at Kocaeli, again protected by FPS, of the "MHP" building at Ankara, provided with STs, and of the Halkapinar Sport Stadium, isolated by LDRBs and VDs (the devices for the last two applications were manufactured in Italy).

Fig. 27. 140,000 m^3 capacities LNG tank at the Aliaga-Izmir terminal of Egegaz (Turkey) protected by 112 LRBs on the borders and 221 LDRBs internally; view of the isolators during installation and of an installed device.

Fig. 28. Retrofit of the Antalya international airport (500 LRBs+SDs).

In addition, two further retrofits are in progress, for the Tarayba Hotel with FPS (to avoid the insertion of shear walls which would make the construction inadequate for its use) and for the Terminal of the Antalya international airport (Fig. 28), where LRBs and SDs manufactured in Italy were installed (this retrofit took advantage of the experience achieved for the upgrading of the Rione Traiano Civic Center at Naples – see Sect. 4.5.1). Finally, two further applications were already designed, for the construction of a second isolated hospital at Erzurum (with LRBs) and the headquarters of the Turkish Economy Bank (with LRBs and LDRBs).

Applications in South Korea

Different from the previously cited countries, South Korea was considered to be a moderately seismic country until recently. However, it has excellent manufacturers of SVPC devices (some actively collaborating with Italian companies) and experienced some important applications of such devices (isolators, dampers and TMDs), partly manufactured in Italy, to numerous bridges and viaducts (20, in addition to approximately 40 new projects, already in 2001) and also to LNG tanks (3 at Inchon and 10 Pyeong-Take terminal, all isolated with HDRBs). The 7.0 magnitude earthquake which occurred on March 20, 2005, with epicenter in the sea between Busan (Korea) and Fukuoka (Japan), by also striking the Korean territory, has led to reconsider the country seismic hazard and will most probably cause the extension of the use of the SVPC systems, also for building application.

Applications in Greece and Portugal

In Greece and Portugal there has already been a significant number of applications of SVPC systems to bridges and viaducts for some years. Most of them make use of devices manufactured in Italy. Nowadays, some important buildings, which are also protected by SVPC devices manufactured in Italy, are being erected. For bridges and viaducts, the Rion-Antirion application in Greece must be cited. There, partly quite large SVPC devices manufactured in Italy were installed in both the main bridge and the approaches (Fig. 29).

Fig. 29. View of the Rion-Antirion bridge in Greece (12 km long), which has been protected by SVPC devices manufactured in Italy (left); some of the 20 Italian transversal VDs installed in the main bridge (force = 3500 kN, displacement = ± 1750 ÷ 2600 mm) (center); some of the 168 Italian transversal and longitudinal VDs in the two approaches (force = 300 ÷ 2400 kN, displacement = ±250 ÷ ±420 mm) (right).

Among the building provided with Italian isolators, it is worthwhile citing: the reticular ceiling of Eleftherios Venizelos international airport at Athens (Greece), isolated in 1998 with HDRBs and multidirectional RBs with sliding surface (Fig. 30); the International Broadcasting Centre, the worldwide largest structure of this kind, located close to the Athens Olympic complex, which was completed in 2004 (before the Olympic Games) using HDRBs (Fig. 31); the reticular ceiling (11,800 m2) of the Akrotiri archaeological excavations in the Greek Santorini island, isolated in 2003 with LRBs and SDs placed at the base of the supporting columns; the "Espirito Santo Unidades de Saude" hospital at Lisbon (Portugal), under construction with HDRBs, installed at the top of the round floor to protect the structure from both earthquakes and vibrations induced by the underground below (Fig. 32).

Fig. 30. International Broadcasting Center at Athens (90,000 m^2 total floor area), isolated with 292 HDRBs manufactured in Italy in 2003.

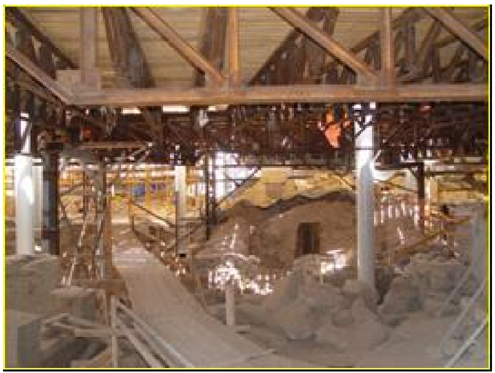

Fig. 31. Reticular ceiling (11,800 m^2) of Akrotiri archaeological excavations in the Greek Santorini island, isolated with 92 LRBs and 2 SDs manufactured in Italy in 2003.

Fig. 32a.

Fig. 32b. Some HDRBs of Fig. 32a.

<u>Applications in Chile, Canada, Mexico and Other Countries</u>

In Chile application of both SI and ED systems has already been performed to bridges and viaducts, some buildings and a few industrial plants: isolated buildings are both strategic (including a hospital) and dwelling. In Canada FDs have been manufactured and used to protect several buildings; such dampers have also been installed in other countries, in particular in the USA (see Sect. 4.4). In Mexico, some buildings were protected by ED systems and an example of SI is that of a Microchip Fabrication Facility at Mexicali, which has been protected by LRBs (similar to the facility located in the USA – see Sect. 4.4).

With regard to further countries, it is worthwhile mentioning that several applications to both bridges and viaducts and buildings make use of SVPC systems manufactured in Italy (similar to those previously mentioned in Taiwan, Turkey, South Korea, Greece and Portugal). Examples of ongoing or planned building applications of such Italian systems are to the new test laboratory of the Skopje University (Macedonia), which is being competed with HDRBs, the Shacolas Park commercial centre at Nicosia (Cyprus), a large mixed r.c. and steel structures to be isolated again with HDRBs, the Medan City Hall a Medan (Indonesia), to be protected by RBs and the Iran Bastan Museum at Tehran (Iran), for which a team of Italian designers, in collaboration with ENEA, designed the retrofit with SI, within a collaboration between Iran and the Italian Ministry of Foreign Affairs (Fig. 33).

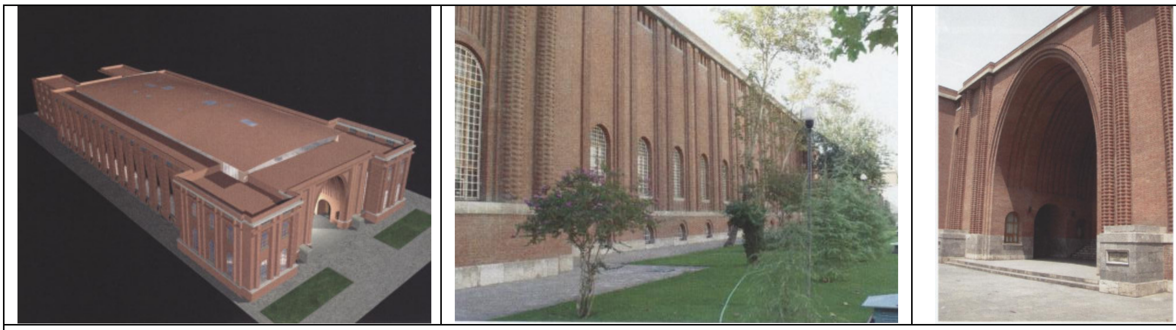

Fig. 33. Sketch and views of the Iran Bastan Museum at Tehran, for which a retrofit design with SI has been developed by a team of Italian designers taking advantage of GLIS and *ASSISi* collaborations.

5. Conclusions

The limits of the conventional seismic design of structures have been clarified. The capabilities of the SVPC techniques to overcome such limits and the main features of such techniques have been summarized. The state-of-the-art of their application has been reported, especially for SI of buildings. In particular, details have been given on the history of the development and application of the SVPC systems in Italy, by showing the leadership it achieved in this field at European level, in spite of the problems suffered until two years ago (first due to the absence of specific design rules, then owing to their inadequacy and the too complicated approval process). The important contribution provided by ENEA to the development and application of the SVPC systems has been mentioned. The present excellent prospects for a wide extension of the use of such systems in Italy, thanks to the new national seismic code and the seismic reclassification of the Italian territory, have been stressed. More generally, the key role plaid by the availability and features of specific design rules on the success of the aforesaid systems in the different countries has been discussed.

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