R&D in Progress at ENEA on the Innovative Anti-Seismic Techniques, with Particular Attention to the Industrial Plants

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ABSTRACT

Reported in this paper are some features of R&D recently performed and in progress at the Italian Agency for New Technology, Energy and the Environment (ENEA) on seismic protection of structures, in particular industrial plants, through innovative anti-seismic (IAS) techniques, namely seismic isolation, passive energy dissipation and semi-active control. This work is being performed in the framework of both new projects funded by the European Commission and a national project funded by the National Research Council. The first (SPACE and SPIDER) aim at the development of floor isolation systems, semi-active systems and systems formed by energy dissipation devices and cables. The second (ISI), to which this paper mainly refers, aims at the development of suitable IAS systems for the protection of high risk components in highly seismic areas and already provided very important results, in particular for tanks containing hazardous materials: in fact, ISI makes reference to a real component, located in a highly seismic Italian site, which will be possibly retrofitted using IAS techniques.

INTRODUCTION

Large R&D efforts are going on in Italy, in particular at the Italian Agency for New Technology, Energy and the Environment (ENEA), on seismic protection of structures, in particular industrial plants, through innovative anti-seismic (IAS) techniques, namely seismic isolation (SI), passive energy dissipation (ED) and active (AC) semi-active control (SAC). This work is being performed in the framework of both new projects (SPACE and SPIDER) funded by the European Commission (EC) and a national project (ISI) funded by the National Research Council (CNR).

ISI, to which this paper mainly refers, aims at the development of suitable SI systems for the protection of high risk plants and components in highly seismic areas. While the EC-funded projects began in March-April 2000, the CNR-funded project began in 1998. It already provided very important results, in particular for tanks containing hazardous materials: for these, the study is being based on a real chemical component, located at a highly seismic Italian site, which will be possibly retrofitted using IAS techniques at the end of the study. Should this pilot application be carried out, it will be the first in Italy to a high risk component and may lead to an extensive use of SI in industrial plants.

The SPACE Project ("Semi-active and PAssive Control of the dynamic behavior of structures subjected to Earthquakes, wind and vibrations") aims at developing new devices for the AC and SAC of the earthquake effects on civil buildings, industrial plants and bridges. This project also includes the development of innovative devices for SI of single floors or parts of buildings containing cultural heritage objects (museums), costly tools (computers) or critical components from a safety point of view (control rooms, surgeries and other hospital facilities). SPACE is coordinated by Maurer-Söhne (Germany); the partnership includes, in addition to ENEA, the German Billfinger+Berger, the Italian ENEL.HYDRO, ENEL.HYDRO-ISMES and "Roma Tre" University, the Swedish Stockholm University, the French Thomson-Marconi and the British TARRC Center.

The most important and innovative aspect of the SPACE Project is the development of semi-active magneto-rheological devices. These devices permit the variation of stiffness and energy dissipation of the SI system using a small quantity of power (only a few Watts). Furthermore, this system provides a basic "passive" behavior that gives the structure a good level of protection also in case of failure of the control system. In particular, these devices make use of fluids with mechanical characteristics dependent on the magnetic field in which they are immerged. During an earthquake the magnetic field can be easily changed using a low current flux controlled by a computer. The computer elaborates data coming from the sensors and intervenes to modify the characteristics of the system to obtain a sort of "intelligent control".

The SPIDER Project ("Strands Prestressing for Internal Damping of Earthquake Response") aims at developing an IAS system based on the use of dampers connected in series with pretensioned cables (Damper Cable System, DCS), which act on the whole structure by reducing the seismic effects on its various floors. This system acts by transferring the whole interstorey drifts of all floors (or sets of them), by means of a special steel cables, to dampers installed at the building base (or only on some selected floors): in this way, dampers are able to dissipate a large seismic energy, since they are subjected to large differential displacements. The cables are pretensioned to keep positive the tension stresses during the earthquake and to provide a re-centering force at the end of the seismic event. DCS is particularly beneficial for retrofit of existing structures, for instance for civil buildings, due to its low cost and easy application.

SPIDER is coordinated by Bouygues (France); the partnership includes, in addition to ENEA, the Italian ENEL.HYDRO-ISMES and Udine University, the French Jarret e VSL and the Portuguese A2P Consult Ltd.

MAIN FEATURES OF THE ISI PROJECT

The ISI Project is devoted to the seismic protection of high risk industrial plants, in particular chemical plant components. While in several countries there are already numerous applications of SI systems to civil buildings (more than one thousand) and to bridges and viaducts, the number of those to industrial plants and components is still rather limited. In particular, very few (none in Italy) are still the chemical plants or components making use of such systems, in spite of their demonstrated large benefits to improve safety without complicating plant layout.

These are the reasons why, in 1998, the Italian Agency for the Environment (ANPA), ENEA and the University of Roma "La Sapienza" jointly undertook a study, funded by CNR, to evaluate the benefits of applying SI to the protection of industrial (in particular, chemical) plants and components. This study includes the following activities:

1. Identification of a reference typical component. The aim is also to make a real SI application possible, at the conclusion of the study. Thus, an existing component had been selected.
2. Analysis of the selected component with regard to both chemical and structural / mechanical engineering aspects, with the evaluation of seismic risk and consequences of possible accidents due to seismic events.
3. Definition of structural and functional requirements of the SI system.
4. Definition of the design vibratory motion for the site where the reference component is installed.
5. Choice of the most adequate SI system for the selected component and its detailed design.
6. Analysis of the isolated component, with evaluation of SI effects on seismic resistance, functionality, layout and costs.
7. Collection of data for general application of results to other components.

The first results of the ISI Project where jointly presented by the partner at the 2nd European Conference on Structural Control [1] and at the 2000 ASME-PVP Conference [2]. The most important are reported below.

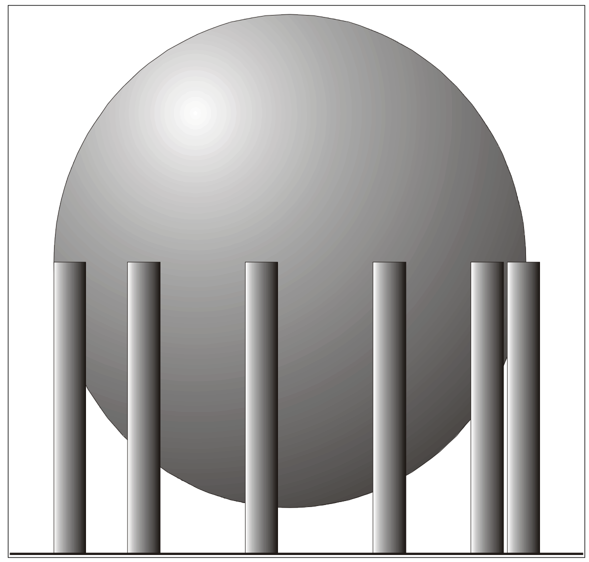

Figure 1: Sketch of the tank selected

SELECTED STRUCTURE

A tank has been selected for the study. More precisely, it is an existing spherical storage tank for liquids, located in the South of Italy. The tank has a diameter equal to 21 m (Volume 5000 m^3) and is supported by eleven 12.5 m high columns, with a diameter of 1 m (Figure 1). The tank walls are 22 mm thick and the total height of the structure is 23.5 m. The mass of the structure depends on the level of liquid in the tank: it ranges from about 310 tons (empty tank) and about 3,300 tons (full tank). Thus, the vertical load acting on the each column varies from about 280 kN to about 3,000 kN. This makes it necessary that great care is devoted to the design of the SI system, as stressed in the following sections.

PROPOSED SEISMIC ISOLATION SYSTEM

In general, a SI system must ensure the following two functions:

1. support the dead load of the structure by avoiding rocking motions during earthquakes;
2. allow for horizontal displacement during earthquakes.

Moreover, a good SI system should also satisfy two further function:

1. provide an adequate restoring force during and at the end of the earthquakes;
2. dissipate a sufficiently large amount of energy.

Aim of function (2) is to move the natural frequency (f) of the structure in a range of the response spectrum which is characterized by a low energy content. This depends on the supported mass M, since $f=\sqrt{(K/M)}$, where K is the total stiffness of the SI system. Thus, in order to have a constant isolation frequency, a SI system with a stiffness proportional to the supported mass would be necessary. Since active control technology is not yet mature for application in the seismic field, especially to high risk plants, the only available system which is able to provide such a behavior is a passive SI system based on friction devices. In fact, the reaction force provided by such SI devices is proportional to the mass through the friction coefficient.

The SI systems which have been analyzed in this study are formed by Sliding Devices (SDs), High Damping Rubber Bearings (HDRBs) or Elastic-Plastic Devices (EPDs). SDs consist of dimpled lubricated PTFE sheets sliding on a polished stainless steel surface, similar to those usually used for SI of bridges and viaducts. For low-speed (thermal) movements**,** the quasi-static coefficient of friction of the sliding elements has been assumed to be μ_s=0.003, while in the presence of high-speed (seismic) movements**,** the dynamic coefficient of friction to be assumed is μ_d =0.01.

In the mixed (HDRBs coupled with SDs) SI system, SDs provide reaction forces and energy dissipation related to the fluid mass contained in the tank, while HDRBs provide the needed restoring force and further energy dissipation. Thus, such an SI system ensures that the previously mentioned four functions are all satisfied.

NUMERICAL MODELS

Two finite-element models (FEMs) of the selected tank were implemented in the ABAQUS code [3]. The first is a simplified model formed by beams, springs and concentrated masses, which has been used for quick parametric analyses. The second is a detailed FEM of the whole structure consisting of over 900 nodes and 850 beam and shell elements (Figure 2), which was used for the final analyses. In both cases the fluid mass was represented by a concentrated mass rigidly connected with the tank wall. Similar model have also been developed and implemented in SAP 2000 code. A simple model with a one degree of freedom oscillator was also used .

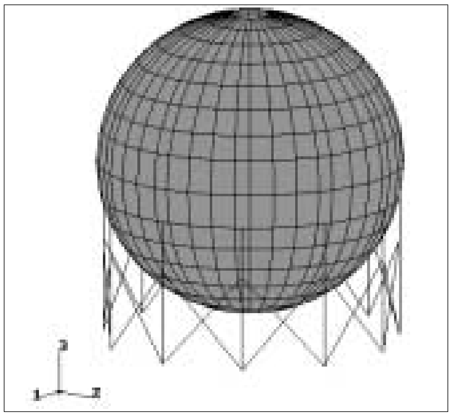

Figure 2: Detailed Finite Element Model

In the calculations, different condition corresponding to empty, full (80% of internal volume filled with liquid, in normal condition) and semi-full (50% of volume filled) has been considered. In a further step of the analysis, the effects of the liquid level and related sloshing-induced forces were also taken into account, according to Nuclear Reactors and Earthquakes standards, Sect. 6.3 (Vibrations of Liquids in Tanks).

The HDRBs (see an example in Figure 3) and the SDs devices were numerically modeled in ABAQUS code by coupling a spring and an elastic-plastic truss, which is a beam working only in the axial direction, that provides the energy dissipation (Figure 4).

Figure 3: HDRB isolation device

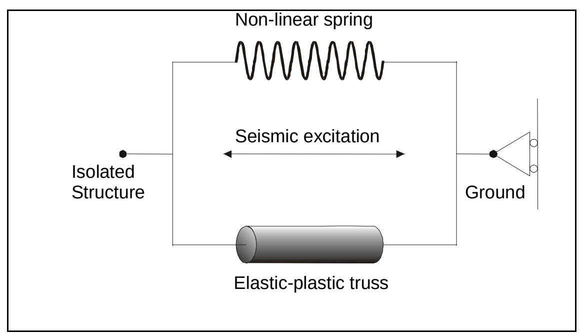

Figure 4: Simplified model of the HDRB

Thus, the hysteresis loop of the HDRB model results to be bilinear, which provides a good approximation of the real behavior. In the SD model, the stiffness of the spring is neglected and the related hysteresis loop simply has a rectangular shape. An example of an EPD is shown in Figure 5, his hysteresis loop is shown in Figure 6.

SEISMIC INPUT

Based on a design response spectrum, which satisfies the requirements of the Italian design guidelines for isolated structures [4] for the site, multiplied by an 'Importance Factor' of 1.4 to take into account the importance of the structure from the risk point of view), several acceleration time-histories were generated and used in the analyses with ABAQUS code.

Figure 5: Elastic-Plastic Device

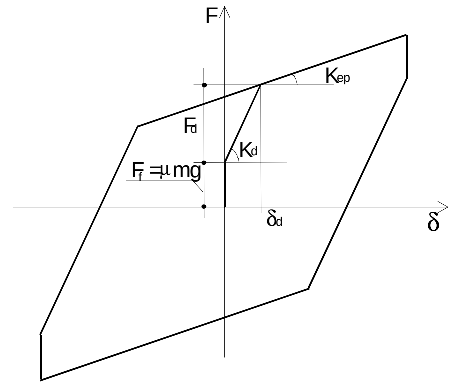

Figure 6: Hysteresis loop of the EPD

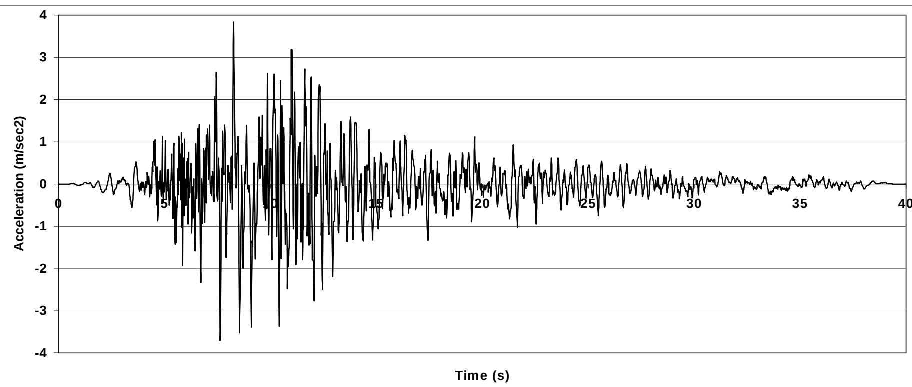

Figure 7: Ground acceleration time-history used in the dynamic analysis

Figure 7 reports, as an example, a 40 s time-history with a peak acceleration equal to approximately 0.4 g. In this way the earthquake considered has a probability of occurring once every 1000 years.

VERIFICATION CRITERIA

In this study, the first yielding of the base of the columns supporting the tank was assumed as a verification criterion of the structure in the analysis performed using the ABAQUS code. Stresses in the columns were evaluated taking into account the dead load of the structure, the maximum bending moment and the shear force calculated during the dynamic analyses.

NUMERICAL ANALYSES

Fixed base configuration.

The detailed and simple models described above were used to evaluate the values of natural frequencies and related participation factors of the tank. Table 1 reports the first 3 natural frequency values in the case of empty and full tanks, in

Table1: First natural frequencies of the tank in the fixed base configuration.

	Frequency (Hz)							
	Empty tank				**Full tank**			
Mode	ABAQUS		SAP	One DoF	ABAQUS		SAP	One DoF
n°	Simpl.	Comp.	2000	Osc.	Simpl.	Comp.	2000	Osc.
1	3.39	3.39	2.78	3.45	1.09	1.10	0.93	1.19
2	3.39	3.39	3.85		1.09	1.10	1.14	
3	4.27	4.16			4.27	4.16		

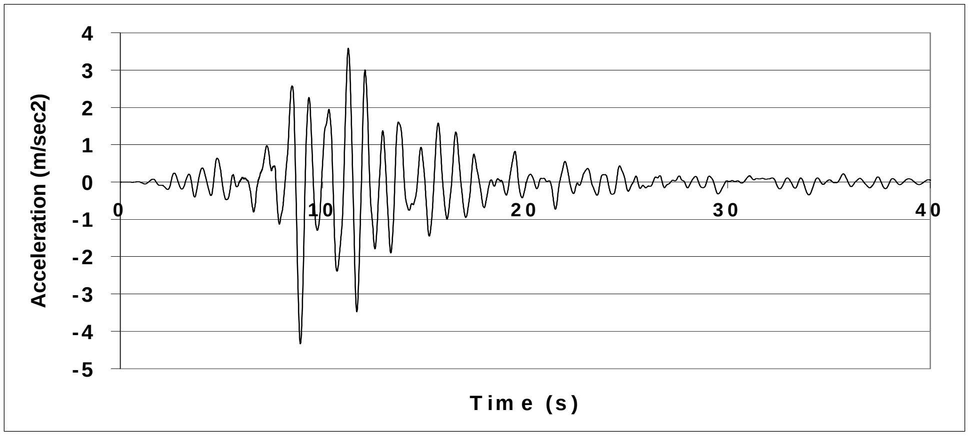

Figure 8: Full tank acceleration in fixed base condition

the fixed-base configuration, which characterizes the tank at present. It is worthwhile noting that the first two bending modes participate with over 95% of the total mass of the structure in the case of empty tank, and over 99% in case of full tank, the third mode is a torsional mode and it is not activated by the earthquake. The comparison of the results obtained by the different models demonstrates that the structure behaves like a single degree of freedom oscillator and that the simplified model can be correctly used. In spite of this simple behavior, the structure must be analyzed using a step by step procedure, due to the non-linear features of the anti-seismic devices.

After completing the modal analysis, some dynamic calculations were also performed on the tank in the fixed-base configuration. It was found that, based on the criteria discussed in the previous section and for the considered seismic input of Figure 7, the structure is positively verified in the case of empty tank. On the contrary, in the case of full tank, the deformation of the columns resulted to be too large and calculations showed that plasticization of the steel occurs.

In Figure 8 is reported the full tank acceleration during the earthquake calculated by ABAQUS with a step by step analysis

Isolated configuration.

Since in the case of empty tank the structure had been positively verified at fixed base, only the case of full tank has been considered for the analysis with SI using ABAQUS code and a step by step integration.

In this analysis the tank was conservatively considered full at 100% of the internal volume. First, a SI system formed by 11 HDRBs (with no SDs) was considered. Two different sizes of HDRBs were analyzed in order to obtain some parametric data on the dynamic response of the structure. The first HDRB (H1) was characterized by a diameter of 800 mm, a rubber height of 100 mm and a shear (G) modulus of 0.8 MPa, which lead to a stiffness of 4,000 N/mm. The second HDRB (H2) had a diameter of 700 mm a rubber height of 150 mm and the same G modulus as H1; thus, the stiffness results to be equal to 2,000 N/mm. In both cases a value of 10% was assumed for the equivalent viscous damping ratio.

The results of dynamic analyses showed a strong reduction of the acceleration of the tank with respect to the input time-history. In addition, the deformation of the devices (about 150 mm) resulted to be very close to the rubber height of the isolator (100% shear strain). However, unfortunately, the deformation of the columns resulted to be too large and the

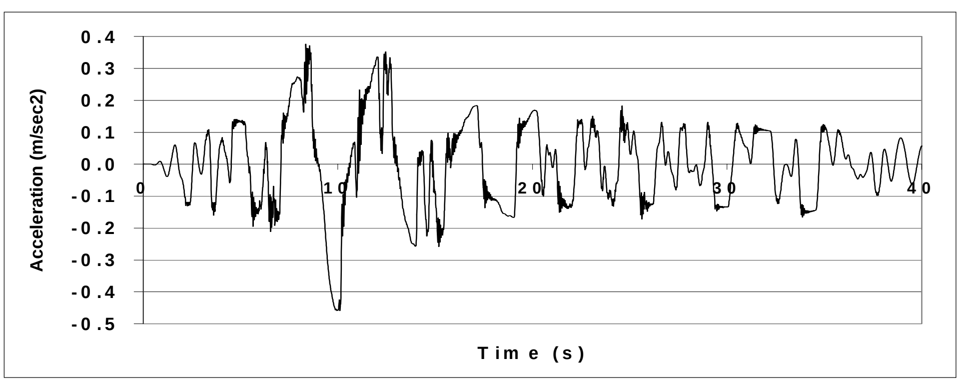

Figure 9: Full tank acceleration in the case 3 H2 and 8 Sliding Devices

verification criteria of the structure were not respected in both cases.

Thus, further analyses were performed with a modified SI system. Since the case of H2 isolators had provided the best results, a softer SI system, formed by sliding devices and HDRBs of the H2 type was considered. In this case also, two different configurations were considered, which were characterized by 5 and 3 type H2 HDRBs, respectively. In this case in order to distribute uniformly the load on the columns, they were connected one with the other by means of rigid bars positioned just above the SI system.

In both cases, the tank acceleration strongly decreased compared to the fixed base configuration, even of a factor 10, in the case with 3 HDRBs, (Figure 9). Moreover, in this case, deformation of the columns was calculated to be 11 mm; and the verification criteria were satisfied. Of course, the deformation of the devices, that is the relative displacement between the structure and the ground, increased. However this increment was not so dramatic, especially in the case with 3 HDRBs. In fact, in this case, the deformation of the HDRBs was calculated at about 190 mm, corresponding to 125% rubber shear strain, which is an admissible value according to the Italian design guidelines for seismically isolated structures [4].

In the last step of the study the effects of the liquid level and related sloshing-induced forces were taken into account. To simulate the sloshing effect, according to Nuclear Reactors and Earthquakes standards, Sect. 6.3 (Vibrations of Liquids in Tanks), a system formed by two concentrated masses substituted the mass of the fluid. One of them, rigidly connected to the tank wall, simulating the part of the fluid that acts as a solid mass and the other, connected to the tank wall by a spring, simulating the portion of the fluid oscillating inside the tank.

Comparing the stress and the deformation of the most loaded column both in fixed base and isolated condition with and without the sloshing effect, we can see that it reduces the stress and the deformation of the columns and increases the natural frequencies.

All the results are summarized in Table 2 in terms of maximum Tresca equivalent stress at the base of the most loaded column and of maximum tank displacement.

Table 2: Summary table for the ABAQUS calculations

Empty	Full 100%	Full 80%	Sloshing	Seismic Isolation	TRESCA Stress MPa	Displac. Mm	Accel. m/sec^2
X				NO	227	26	12.3
X				3 HDRB + 8SD	99	71	1.60
	X			NO	901	107	4.12
	X			11 HDRB H=100	341	187	1.57
	X			11 HDRB H=150	346	199	1.14
	X			5 HDRB +6 SD	264	232	0.68
	X			3 HDRB +8 SD	215	205	0.42
		X		NO	758	90	4.33
		X	X	NO	660	77	5.14
		X		3 HDRB +8 SD	183	187	0.46
		X	X	3 HDRB +8 SD	161	118	0.52

Different solutions were studied using different models. The SAP 2000 model was used to analyze the present situation for full, semi-full and empty tank, finding that the full tank is not able to withstand the design earthquake, and than used to study a SI system formed by 11 HDRB with 600 mm diameter and 156 mm high rubber.

Also with the SAP 2000 model the sloshing effect was analyzed, following the mentioned standards, and finding that the sloshing has a positive effect in reducing the stresses at the columns base.

Table 3: Results of SAP 2000 analysis fixed base and isolated (in brackets) tank

Tank analysis	1st Period s	2nd Period s	$\sigma_{max.}$ at the column base Mpa	σ_{min} at the column base Mpa	Max Tank Displacement cm
Full without sloshing	1.08 (3.08)	0.880 (2.5)	380 (-12)	-532 (-160)	9.7 (21.8)
Full with sloshing	4.63 (4.93)	0.86 (2.26)	278 (-58)	-425 (-115)	7.6 (16.3)
Semi-full with sloshing	5.30 (5.23)	0.59 (1.59)	194 (-36)	-295 (-76)	5.3 (12)
Empty	0.36 (1.03)	0.26 (0.8)	129 (10)	-147 (-30)	2.9 (9)

The results of the SAP 2000 analysis are summarized in Table 3, in brackets are indicated the value for the isolated tank. It is possible to see that the isolation has strongly positive effects in all the situations evaluated.

Using the simple one degree of freedom (DoF) oscillator model, several situations were studied. First of all it was used to evaluate the actual situation with the tank rigidly connected to the ground. A conventional base isolation with Rubber Bearings (RBs) was than analyzed. The RBs are schematized adding a new spring with stiffness K_d to the spring with stiffness K_s simulating the structure stiffness, (Figure 10), where C_s is the structure damping). The results are reported in Table 4 in terms of oscillation period and total shear force at the base of the columns.

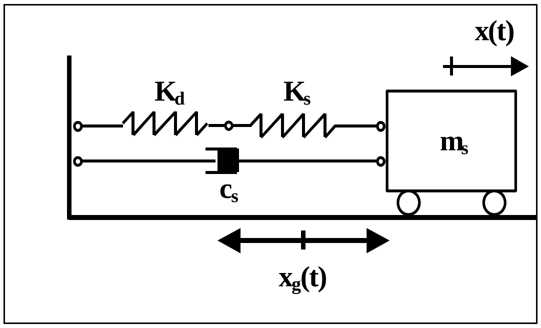

Figure 10: Simplified model for base isolation with Rubber Bearings

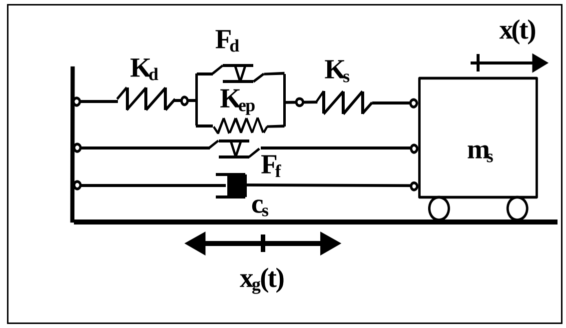

Figure11: Simplified model for base isolation with Elastic-Plastic Devices

Table 4: Results of one degree of freedom analysis for base isolation with Rubber Bearings

Load Condition	80%	50%	Empty
T (s)	3.00	2.24	1.00
F (kN)	2900	2250	1000
Displacement (m)	0.243	0.181	0.080

The second solution foreseen an increase of the dissipation of the structure by means of internal or external device (Figure 12). In this case, due to the mechanical characteristics of the structure, the reduction of the lateral load induced by the seism is not sufficient, thus this solution was considered not suitable for this type of application.

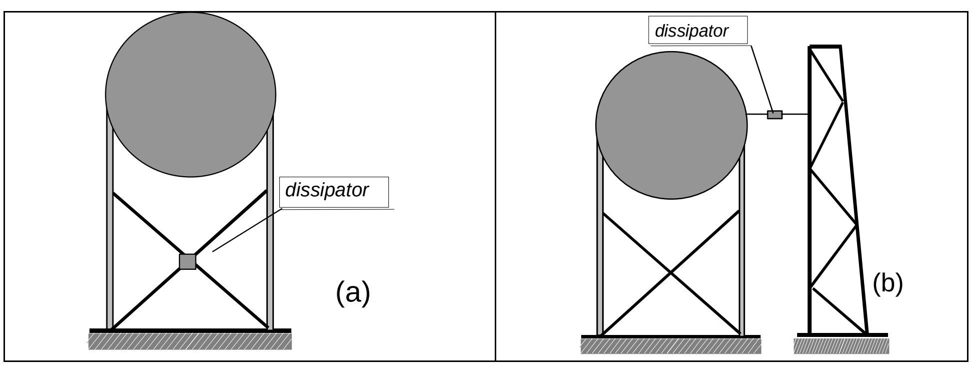

Figure 12: Internal and External Dissipative Devices

The third solution studied considered the application of elastic-plastic devices (an example is shown in Figure 5), positioned between the base of the columns and the foundation. These devices are largely used in bridges and viaducts and their aim is to change the natural frequencies of the structure but, above all, to increase the dissipation capability of the structure. Their hysteresis loop is shown in Figure 6 where K_d is the initial elastic stiffness, K_{ep} the secondary elastic-plastic stiffness, F_d the yield force, F_f the friction force, δ_d the yield displacement. These devices are introduced in the single DoF model as shown in Figure 11. Some parametric calculations were performed with different values of the elastic stiffness K_d, of the friction coefficient μ and of the plastic stiffness K_{ep}.

The best design solution to reduce the shear force and the mass displacement was the one with $K_d=0.5K_s$. In Table 5 the results obtained with $K_d = 0.5K_s$, $\mu = 0.01$ and $K_{ep} = 0$ are shown in terms of period of oscillation, total shear force at the columns base, displacement of the tank as regards to the device and displacement of the tank.

Table 5: Results of one degree of freedom analysis for isolation with Elastic-Plastic devices

Load Condition	80%	50%	Empty
T (s)	1.45	1.09	0.50
F (kN)	1195	1080	961
Displacement (m)	0.144	0.061	0.041
Rel. Displacement (m)	0.006	0.006	0.006
Acceleration (g)	0.050	0.080	0.325

A summary of the most promising solutions proposed, in terms of total shear force at the base of the columns and tank displacement reported in Table 6.

Table 6: Comparison of the different solutions

	Total Shear Force (kN)		Displacement (mm)	
	Full	Empty	Full	Empty
Fixed Base	14400	3890	90	32
11 HDRB	2900	1000	243	80
Mixed	1260	470	187	71
11 EP	1195	961	144	41

CONCLUSIONS

The main features of ongoing EC-funded projects (SPACE and SPIDER) on the development of IAS techniques, which involve ENEA, have been shortly summarized. More details have been provided on the ISI national project; in particular, the benefits of SI of an existing spherical tank were analyzed in this study. Different SI systems were considered by ANPA, ENEA and the University of Rome "La Sapienza". The most promising solutions resulted to be a system formed by 3 HDRBs (acting as isolators, dissipators and re-centering devices) and 8 SDs (acting as isolators and energy dissipators) and a system formed by 11 EPDs. The mixed SI system provides a sufficient restoring force and an energy dissipation related to the fluid mass inside the tank, but with a displacement of about 200 mm during the earthquake. The SI system formed by 11 EPDs offers a lower displacement during the earthquake, but with a small residual displacement after the earthquake (about 40 mm). Both the systems offer a strong reduction of the forces transmitted to the structure during the earthquake. Being the benefits of the SI system confirmed, it might be used to really retrofit the considered tank.

The ISI project is fully consistent with the recommendations of the 6th International Post-SMiRT Conference Seminar on Seismic Isolation, Passive Energy Dissipation and Active Control of Vibrations of Structures held at Cheju (Korea) in 1999, [5] where the importance of application of the IAS techniques to chemical plants had been stressed.

ACKNOWLEDGMENTS

The authors warmly thank their colleagues of ANPA (Dr. T. Sanò and A. Pugliese) and University of Rome La Sapienza (Prof. V. Ciampi and Dr. D. Addessi) for having made available their results for comparison with those of ENEA.

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