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PASSIVE CONTROL FOR SEISMIC PROTECTION OF CRITICAL COMPONENTS IN INDUSTRIAL PROCESS PLANTS

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SUMMARY

The paper reports a methodology of approach and some preliminary results of a recently undertaken research activity, aimed at the evaluation of the benefits which might derive by the use of passive control techniques for the seismic protection of critical equipment and components in industrial process plants.
After presenting a classification of such equipment and components, using a seismic risk point of view, and a short survey of some recently observed earthquake induced failures, and of their consequences, a couple of application studies are briefly reported. The first one is a seismic retrofitting case-study of a spherical butane storage tank, by means of different passive control techniques; the other is the experimental study and validation of a new steel bracing system which, for its characteristics, appears particularly fit to be used in applications related to industrial plants.

INTRODUCTION

In recent years there has been a growth of applications of innovative techniques to the seismic protection of structures, both for new constructions and for the retrofitting of existing ones; they are based on the concepts of structural vibration control, in its different forms. Particularly effective, for their simplicity, dependability and low cost, are the passive control techniques, in particular base isolation (BI) and passive energy dissipation (ED), which have found large application in many high seismic risk areas, in particular in Japan, New Zealand and United States. If compared to the number of existing applications in the field of civil constructions, the ones regarding industrial plants and components are still relatively few; in particular a very small number of applications exist worldwide which relate to process plants (chemical, petrol-chemical, …), even though the risk of major accident to population and the environment, which may follow from an earthquake striking such plants, is well acknowledged.
The authors have become recently involved in some research projects, funded by the Italian National Research Council (CNR), and by the Italian Institute for Prevention and Safety in the Work Environment, (ISPESL), aimed at the evaluation of the benefits which may be expected by the application of BI and ED systems to the seismic protection of process plants and equipment.
This presentation reports on some of the first activities of these projects.

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The paper develops according to the following lines. First of all a typological classification of the industrial plants, with reference to their sensitivity to seismic risk, is proposed; attention is then focused, in particular, on process plants, for which a detailed exam and classification of typical equipment and components is given, together with a brief discussion of observed, earthquake induced, damage and failures. This is used as a starting point to operate a rational selection of a number of significant components, for which it appears worth to conduct detailed seismic vulnerability case-studies and to propose and verify the effectiveness of the application of different passive control technologies.
The first typology selected, at this stage, comprises very common equipment, such as elevated tanks, furnaces and similar, which share the particularity of presenting a main body, of significant size and weight, which is kept elevated with respect to ground by rows of single supporting columns; this kind of structures has been observed to be easily subjected, as a consequence of an earthquake, to typical soft first story failure modes. The first application of passive control techniques, presented in the paper, refers, therefore, to one of these structures, in particular to a spherical elevated tank, and is essentially a numerical case-study. A second application, instead, is essentially experimental and regards the proposal, testing and validation of a new dissipative bracing system which, for its peculiar characteristics, appears to be particularly suitable for applications to typical structures of process plants.

A SEISMIC RISK RELATED CLASSIFICATION OF INDUSTRIAL PLANTS

Mechanical plants: a wide variety of purposes and design is present in this category which includes heavy carpentry workshops, machinery factories, servicing lines, etc. This kind of plants are generally characterized by large and heavy machines. The impact of an earthquake produces structural effects localized within the plant itself, which can cause in the worst cases the collapse of the entire plant. Releases of significant amounts of dangerous materials in the environment are however rather unlikely and generally limited to flammable products, whose consequences can be also limited to local fires.
Power plants: these installations are directed to the production of electrical energy using fossil or nuclear fuels as the primary source. Their general structures are quite similar, the main differences being those strictly related to the fuel peculiarities. In all cases, in facts, they are characterized by large and heavy equipment. The impact of an earthquake still produces structural damage effects localized within the plant with the limit possibility of full collapse of the equipment. The risk of dangerous releases toward the environment is strongly dependent on the fuel used. In thermal power plants using liquid or gaseous fuels the damage of equipment or piping determines the release of significant amounts of flammable material so that serious fires can develop, both in the operating zone, to which the fuel is fed in continuous, and in the storage areas where large amounts of liquid fuels are present; the consequences of such events remain however local. In the nuclear power plants any damage to the reactor, which is the central element of the plant, could lead to the release of radioactive materials which can easily contaminate a very large extension of territory; for these reasons, since the very beginning of adoption of the nuclear source, the construction of power plants has been accompanied with serious studies of seismic vulnerability. Seismic impacts may involve also subsidiary components of the power plants such as voltage transformation substations and electric transport lines; in these cases, however, the consequences are strictly local. An indirect but also serious consequence of the power system damage is the interruption of electric energy production and distribution, which may interest large portions of territory, with the risk of several and various domino effects.
Process plants: this denomination includes all the installations performing chemical and/or physical-chemical transformations of the materials. The typology of equipment is very heterogeneous and complex and is characterized by a large variety of specific configurations, operative conditions and substances processed. It is then not easy to work out a simple scheme of the typologies of equipment belonging to this class, because they vary from case to case, depending on the process parameters required: different pressures, temperatures, masses of substances and, sometimes, the possibility of obtaining the same final

product by different sequences of operations, determines different equipment and different layout arrangements. In addition the process conditions inside the equipment and the piping system induce variable stresses to which the seismic ones are added. The consequences of seismic forces on the equipment and piping of a process plant are very different and vary dependent on the specific situation. Quite often these consequences are critical and they consist in releases of dangerous – corrosive, explosive, flammable and/or toxic – substances. The extension of the consequences could interest the plant itself with escalation effects to the surrounding of the plant even tens of kilometers far.

PROCESS PLANTS: A CLASSIFICATION OF EQUIPMENT AND COMPONENTS

Based on the previously developed considerations, process plants appear as the ones which need more attentive consideration with regard to seismic risk. In attempting to present a classification of their typical equipment and components, three functional macro-categories may be distinguished first:

Process units: they are the units where chemical and/or physical-chemical transformations occur. In most cases these units are metallic vessels, with slim cylindrical shapes, vertically oriented and relatively deformable; different shapes are however possible for specific pieces of equipment. Only in few cases masses are considerably high.

Storage units: they are structures predominantly metallic, characterized by low height/diameter ratios and by large masses, essentially due to the contained substances. The equipment more vulnerable to earthquakes are those containing liquids because of possible increase of forces on the walls caused by the sloshing liquid. This effect is much less in case of solid materials, for which the inter-granular mobility is limited, and for gaseous substances because of their little density.

Pipelines and pipe systems: they have the function of conveying the materials from a process unit to another, assuring always their confinement. Most of the piping, within the plants and offsite, for long and medium distance transportation, is metallic. Pipes can be installed above ground or underground. Those above ground are usually grouped in parallel bundles supported by racks and provided with special components to allow the compensation of the thermal expansions, driven by special constraint devices. In most cases the pipes are subjected to service vibrations induced by the pushing machines, as pumps and compressors, especially when they are of the reciprocating type. Large diameter underground pipelines are very common especially for transportation of natural gas and oil. They are particularly vulnerable to earthquakes because of their length and stiffness, taking also in consideration the possible difference of the seismic input at different points. A damage and the consequent release could not be easily detected and controlled due to the fact that the pipelines are not immediately visible. In specific cases the use of materials like cast iron, ceramics, glass, concrete, etc., is required mainly for reasons of corrosion resistance; in such cases the fragile properties of these materials deeply increase the risk of cracks even under moderate earthquakes.

A different classification of the equipment and components may be done considering their peculiar structural aspect. This leads to the following distinction:

Slim vessels: they are cylindrical pieces of equipment showing a high height/diameter ratio (typically 5:1 to 20:1 and even more, in special cases). Among them, in relation with their process function and with the system of constraints to which they are subjected, it is possible to identify:

- Slim vertical vessels which are directly anchored to foundation (single basement) and free all along their height. This category includes the columns (or towers), many reactors, many metallurgical furnaces, some stacks. For all these equipment the concentration of mass (whole mass/whole volume ratio) is not high;

- Vertical vessels which are directly anchored to foundation (single basement) and present additional constraints along their height. In this category there are particularly thin columns, some stacks and practically all flares, which are sustained by reticular stiffening structures (Figure 1), or by one or more orders of stays. The whole mass is limited in comparison with the volume for the reason that the fluid inside is essentially a gas.
- Horizontal cylindrical vessels supported by two or more saddles connected to a foundation platform. This category contains the typical process storage vessel and little and medium pressurized storage vessels, shell-and-tube heat exchangers, furnaces, rotary drums. The concentration of mass is considerable for storage vessels and heat exchangers, which have high content of dense fluids and structural mass respectively. Rotary drums, on the contrary, are characterized by a low degree of filling.

Figure 1: Tall flare within a stiffening structure

Squat equipment directly sitting on a foundation, with or without an anchorage. These vessels are characterized by similar dimension in the three space directions and by heavy mass. It is possible to distinguish the following sub-categories:

- Large atmospheric storage vessels for liquids: they are vertical cylindrical vessels with a height/diameter ratio (2:1 up to 0.2:1). The bottom plate is circular and uniformly sitting on foundation. The roof can be welded to the shell (fixed conic roof) or floating over the contained liquid. The operating volume varies from some tens to 200000 m^3. When they are full, they present a considerable mass. In case of an earthquake the oscillation induced on the upper part of the liquid mass can generate a sloshing effect, which produces high impact actions against the thin shell.
- Large process static machines (filters, decanters) and dynamic machines (pumps, compressors). These pieces of equipment are characterized by high mass and a squat structure. They need high inertia foundations, even because of the dynamic stress that they produce under service conditions.

Squat equipment supported in elevation by columns. In this category there are some specific process and storage equipment:

- Spherical storage vessel (Figure 2). They are essentially storage vessels used for pressure liquefied gases. They are elevated with respect to ground, supported by a number of circumferential legs welded to the shell at the equatorial level and normally linked each-other by diagonal braces. The capacity of these tanks usually reaches 10000 m^3 and even more in sporadic cases. The height of the legs depends basically on the size of the sphere. In case of an earthquake, the elevation of the equator and the slimness of the legs are responsible for the large bending stresses on the legs, which may lead to a

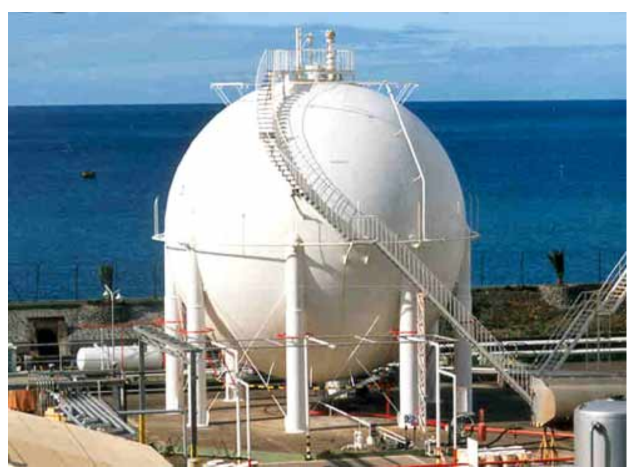

Figure 2: Spherical butane tank

collapse of the structure.

- Vertical large storage vessels for cryogenic liquefied gases (Fig.7). The general configuration of these storage vessels, operating at atmospheric pressure and with maximum capacity up to 25000 m^3, is similar to that of the large atmospheric storage vessels for liquids above mentioned. Two main differences, required by the extremely low temperature of the stored product, consist in the presence of a double shell, in the inter-space of which an efficient thermal insulation is located, and in the fact that the bottom does not sit directly on the ground but is anchored to a flat concrete platform, supported in turn by a number of short legs, which keep the tank slightly elevated with respect to the ground. In case of an earthquake the horizontal forces may induce shear failure of the legs. In addition the sloshing of the liquid inside the vessel can generate localized compression and elephant foot deformations.
- Process furnaces and steam boilers. These equipment have the function to heat or vaporize large amounts of liquid products, thus requiring high thermal rate and/or relatively high temperatures. Process furnaces are structures with generally large size, with few standardized shapes, mainly box (or cathedral) and vertical cylinder (Figure 3). The furnaces must be kept elevated from the ground by means of two or more rows of columns because of maintenance requirements of the burners and of the piping placed below the bottom. The elevation of the furnace bottom ranges 2-2,5 m. In case of an earthquake, large bending and shear effects may be generated at the contact surface between the columns and the bottom plane. Big steam boilers present a similar configuration.

Figure 3: a) Box-shaped furnace, b) Cylindrical furnace

Piping and pipelines. The most sensitive points of a pipe are the joints to a variety of line accessories (valves, line filters, instrumentation, supports, thermal expansion and vibration dampers, etc.) and the connections to pieces of equipment, which are singular points of variation of resistance, or of concentration of masses. Seismic actions can drastically increase the frequency of cracks and loss of containment from discontinuities, which is frequent even under service conditions.

The seismic behavior of buried pipelines and piping systems is quite different from that of the above-ground pipes. Some of the differences are here summarized:

- For underground long pipelines the horizontal inertia forces are largely contrasted by the surrounding soil; the relative movements between pipe and soil is responsible for inducing stresses at the joints.
- The damage of an above-ground structure, even if it can be the initiating event for a domino effect, is immediately detectable and therefore generally restricted to that structure alone, while the damage at a certain location within a network of underground pipelines will affect other portions of the system.

EARTHQUAKE INDUCED FAILURES OF CRITICAL EQUIPMENT IN PROCESS PLANTS

The most documented earthquake failures of critical components and equipment in process plants refer to tanks, to all kinds of leg supported heavy structures, and to pipelines, (Moat [1], Iwatsubo [2], Erdik [3], Datta [4]).

Tanks

Tanks, in general, have not performed well in recent earthquakes. Most of them have been seriously damaged.

Flat-bottomed tanks

The documented effects of the earthquakes on this type of tanks are:

- Separation of the tank wall with respect to the floor;
- Anchor bolts breakage;
- Ripping of the tie down strap;
- Excessive displacement of the bottom of the shell and breakage of the connection pipes;
- Bouncing of the floating roof due to the sloshing of the fluid and consequent impact on the shell causing sparks which can ignite flammable substances inside (Figure 4);
- Elephant foot buckling of the tank (Figure 5);
- Deformation of fixed roof;
- Inclination of the tanks due to liquefaction of the soil;
- Deformations and collapse of accessories: breakage of connecting bridge among adjacent tanks;
- Falling of connected flanges and valves.

Figure 4: Floating roof tanks destroyed by a huge fire

Tanks supported in elevation by legs

The main problems of these structures are:

- Soft first story effect at the interface between the legs and the tank with possible collapse of the sustained structure;

- Tear at the connection of the shell and supporting legs;
- Buckling of the supporting legs (Figure 6);
- Excessive displacement at the connection pipes and possible loss of seal or mechanical fracture in correspondence of weak points.

Figure 5: Elephant foot buckling

Figure 6: Buckling of the supporting legs

An important history case involving spherical tank is the one occurred at the Paloma Cycling Plant in Kern County near Bakersfield in 1952. Two of the five large butane spheres collapsed with the rupture of the pipework and determining a major release. A large vapour cloud was formed and ignited some minutes later by one transformer one hundred meters far. There was a violent vapour cloud explosion followed by a major fire.

Other leg supported equipment (Liquefied cryogenic gas storage tanks, furnaces)

A failure of the supporting system is also well documented for cryogenic liquid oxygen tanks (Fig. 7). This event caused the loss of 1200 metric tons of cryogenic liquid oxygen and determined the loss of refrigeration capacity.
Similar failure has been also reported for furnaces.

Figure 7: Failure of the concrete pillar support of two cryogenic liquid oxygen tanks.

Pipelines and piping

Buried pipelines
Field observations and various studies indicate that major seismic hazards to buried pipeline systems are:

- Excessive axial and bending stresses and deformations in pipelines, created mainly by the phase difference, and change of wave shape between different points along the pipeline;
- Large displacements resulting from the fault movement during an earthquake, if the pipeline crosses a major fault;

- Landslides and buoyancy caused by soil liquefaction.

Above ground pipelines and piping systems

- Tumble of meters and pumps due to vibrational excitation;
- Failure of tie-rods, spring hungers, and expansion joints;
- Leakage of fluid from junctions;
- Inclination and collapse of pipe support structures;
- Damages of the lines at the couplings between tanks and pipes, because tanks and pipes move independently under seismic stress due to their respective proper periods of oscillation.

USE OF PASSIVE CONTROL TECHNIQUES IN INDUSTRIAL PROCESS PLANTS

Important applications of passive control techniques to equipment typical of industrial process plants are mainly reported, up to now, for large cylindrical tanks directly sitting on their foundation, which, in a number of cases, have been base-isolated.

Some applications of the energy dissipation concepts, which originate in the Nuclear Power Industry, may be easily transferred to the process industry field, such as, for example, some special dissipative supports or restrainers for pipelines, or a particular base isolation system, in combination with elastic-plastic restrainers, which has been proposed for the seismic protection of a steam generator Bhatti [5].

Another energy dissipation technique, which is worth being explored, is the use of energy dissipating connections between adjacent structures. This may be beneficial, for example, in the many cases where, in the traditional design, it has been already recognized the need for using a stiffening structure to control a very flexible component, (Fig.1). The traditional rigid connections may be advantageously substituted, in fact, by energy dissipation devices. A companion paper presented at this Conference reports on an experimental study which refers to this kind of arrangement, Cimellaro [6].

Taking into account the existing knowledge, the state of applications and all the previously made considerations, it has appeared significant to concentrate first, at this stage, on a particular, very common, structural typology, which does not seem to have received sufficient attention. This is the case of equipment supported in elevation by columns, which is predisposed to soft first story failure modes. For this case both main passive control techniques, Base Isolation and Energy Dissipation, appear able to offer effective seismic protection, (see for example the schematic indications in Figure 8)

The two research studies, which are briefly mentioned in the following of the paper, are, therefore, directly connected with the above said case.

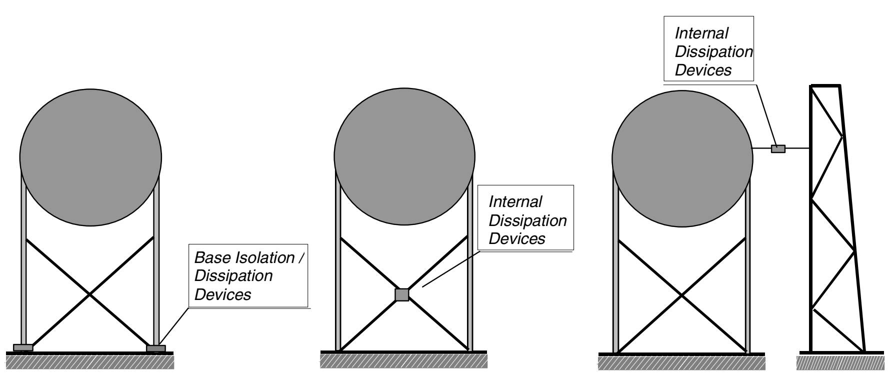

Figure 8: Different passive protection systems

SEISMIC RETROFITTING CASE-STUDY OF AN ELEVATED SPHERICAL TANK

Both seismic protection technologies based on passive control, base isolation and energy dissipation have been considered for the retrofitting case-study of a spherical tank, (for details see Ciampi [7]). In particular, the following systems have been studied and compared: Base Isolation using High Damping rubber bearings (HDBI), Energy Dissipation at the Base of the structure using dissipation devices in connection with low friction sliding bearings (BED), Internal Energy Dissipation using dissipation devices in properly selected position inside the structure (IED). In Figure 8 the different techniques are schematically illustrated. In particular, two solutions are indicated for the Internal Energy Dissipation, one which modifies the existing traditional bracing system, by substituting it with a dissipative bracing system, the other which introduces an external stiffening frame.

The existing steel spherical tank (Figure 9), containing a liquefied gas, butane, is supported by eleven steel cylindrical columns linked by diagonal steel braces. The tank is characterized by the following geometrical properties:

external diameter	D_e = 21.1650 m
thickness of the tank walls	S_{wt} = 0.0220 m
height of the sphere centre	H_s = 12.8700 m
external diameter of the columns	d_e = 1.0660 m
thickness of the column walls	S_{wc} = 0.0095 m
height of the columns	H_c = 12.5000 m
area of the diagonal braces	A_b = 9.62E-4 m^2
height of the diagonal braces from ground	H_d = 6.8100 m

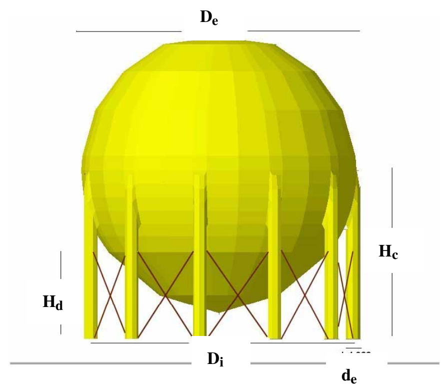

Figure 9

Considering the weight density of the butane equal to 6 kN/m^3, the 80% filled tank has a total weight P = 26750 kN. The response spectrum proposed by the Italian Design Guidelines for Seismically Isolated Structures (CSLLPP, 1998) has been adopted to artificially generate six acceleration time-histories, whose peak value has been chosen equal to 0.25 g, after consideration of the site where the structure is placed. In the numerical analysis an *Importance Factor* of 1.4 has been also taken into account, in consideration of the relevance of the structure from the seismic risk point of view.

Simplified one degree-of-freedom models

Simplified analyses of the dynamic behaviour of single degree of freedom (SDOF) models, representing the spherical tank in the actual state and in the retrofitted configurations, have been conducted first, with the objective of comparing the effects of the different passive control techniques on the overall behaviour of the tank, in terms of global response quantities, such as total base shear and characteristic displacements.

The mechanical properties of the models are: the total mass $m_s = P/g$, which includes the weight of the structures and of the content, for the 80% filled case; the stiffness K_s, which is computed by considering both the columns and the tension-only diagonal braces; the damping coefficient c_s, which is evaluated on the basis of an assumed structural damping ratio, ξ_s =2%. With reference to the retrofitted case, for both base protection techniques, isolation and dissipation devices may be modelled by a single nonlinear element, with an essentially elastic-plastic constitutive law, which links the elastic spring, representing the supporting system of the tank (columns and braces), with the ground. The finite element code SAP 2000, which handles concentrated nonlinearities, is used to perform the analyses. All the results have been averaged over the set of the six artificially generated acceleration time-histories.

Un-retrofitted tank

The SDOF model which represents the structure in the un-retrofitted situation, is assumed to have elastic behaviour. This produces a natural period T = 1.11 s. The corresponding computed maximum response quantities are, for this case: base shear F = 11945 kN, and mass displacement x = 0.137 m.

Base isolation 1 (High Damping Rubber Bearings)

Base isolation is assumed to be implemented by introducing, at the base of the eleven columns, commercially available high damping rubber bearings (HDRB), made of rubber layers and steel reinforcing plates, whose constitutive behaviour is well described by an elastic-plastic-hardening model with elastic stiffness K_e, yield force F_y, post-yield stiffness κ times K_e, (κ hardening coefficient). The mechanical properties of the isolator are designed so that the period of the structure, in the isolated configuration, (based on post-yield stiffness), is close to 3 s.

Taking into account the available production data of HDRB isolators, the following values result for a single one of them:

$$K_e = 14500 \text{ kN/m} ; \qquad F_y = 47.5 \text{ kN} ; \qquad \kappa = 0.1,$$

with the corresponding geometrical characteristics:

total height: 0.274 m; rubber height: 0.156 m; diameter: 0.600 m.

Structural period, and peak values of base shear, mass displacement and column deformation, obtained from the numerical analysis for this base isolation design, are respectively:

$$T = 2.82 \text{ s}, \quad F = 2388 \text{ kN}, \quad x = 0.148 \text{ m}, \quad x_{\text{rel}} = 0.027 \text{ m}.$$

Comparison with the un-retrofitted case shows the shift towards higher values of the period, the considerable reduction of the base shears, and, as a consequence of the high damping characteristics of the isolators, the only modest increment of the mass displacement.

Base isolation 2 (Energy dissipation at the base)

A different BI solution is directly based on the introduction of energy dissipation devices at the base of the eleven columns, in connection with standard low friction sliding bearings. The steel energy dissipation devices are of the typology shown in Figure 10; they have been developed and tested at the University of Rome “La Sapienza”, Ciampi [8,9], and employed, (Figure 10a), as protection systems for important bridges. In Figure 10b a single “C” shaped device is shown, together with the schematic assemblage of a set of 3, as possible multiple device configuration, to be used at the base of the columns. The dissipating device is cut out of a steel plate and its dissipation mechanism is activated by the flexural elastic-plastic in-plane deformations. The assemblage of multiple devices, as shown in Figure 10a-b, is functional to get symmetrical performance in the radial direction.

The hysteretic behavior of the assemblage, (dissipation devices + low friction bearings), is described by the same elastic-plastic-hardening constitutive model used for the

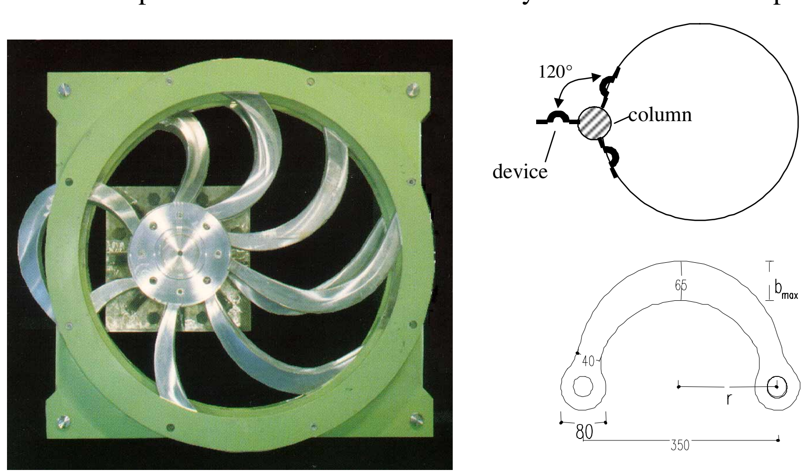

Figure 10: Steel Elastic-Plastic Device (EPD) and assemblage.

HDRB, but with properly different mechanical parameters and the addition of a friction coefficient β.

The design of the dissipation devices is performed by using an energy based methodology, from which design spectra have been constructed, Ciampi [10]. The stiffness K_d of the dissipation devices is selected first, as $K_d = K_s/2$, and the corresponding modified period of the structure, T_d = 1.92 s, is computed; by using the above mentioned design spectra, the normalized yield force is then selected, η_d = 0.1, to which corresponds F_d = 930 kN. Taking into account the particular configuration proposed for the assemblage of the three devices, (Figure 10b), the stiffness to be assigned to each one is equal to $K_\mathrm{d}/1.38$, while the yield force is $F_\mathrm{d}/1.85$. By assuming to use a low-carbon steel, with yield stress 360 MPa, the following dimensions are obtained for each device:

diameter: 0.520 m; thickness: 0.030 m; maximum width of the "C" section: 0.068 m.

Peak values of base shear, mass displacement and column deformation computed for this case are:

F = 1360 kN; x = 0.13 m ; x_rel = 0.015 m.

It has to be noted that, compared to base isolation with HDRB, this protection system, shows a better performance, producing lower values of both base shear and mass displacement.

Internal energy dissipation by means of dissipative bracings

An approximate analysis of systems based on internal dissipation devices has been also performed. Under the simplified hypothesis that the introduction of energy dissipation devices in a structure increments only the dissipation capacity, while leaving unchanged the stiffness properties, it is possible to get a quick, approximate, estimation of the added damping effect, by using one of the many available spectrum reduction formulae. In this case, considering that the effect of the internal dissipation devices corresponds to an equivalent damping ratio ξ_s = 15%, the following results are obtained:

F = 7334 kN; x = 0.084 m.

With respect to the un-retrofitted case both forces and displacements are reduced (about 40%), but the overall result appears less satisfactory than the ones of Base Isolation 1 and 2. On the other hand, values of the damping ratio higher than 15% would not be much more effective and appear very difficult to be achieved. This protection system is not able to produce the very high reductions of base shear which would be desirable for the case considered, where the actual structure has a very low lateral resistance which makes it very vulnerable to seismic actions. The internal dissipation technique is more suitable for retrofitting structures which present more favourable initial conditions.

Detailed finite element analyses of the tank behaviour

Comparison of the different passive control systems has shown that Base Isolation 2 gives the best result in terms of base shear reduction, while only Internal Energy Dissipation, (dissipative bracings), is able to produce a substantial reduction of the total displacement; of course in this last case, with no physical separation at the base, all the displacement go, as in the un-retrofitted case, into deformation of the columns, while in both Base Isolation cases most of the displacement concentrates at the isolator/dissipator level.

The simplified SDOF system analyses have given useful indication for selecting Base Isolation 2 as the optimal retrofitting system. A subsequent more detailed finite element analysis is necessary to understand the detail of the local behaviour. An example of the results of such analysis is presented in Figures 11-12, where stress distributions in the tank may be compared for the two cases, un-protected (Figure 11) and protected with Base Energy Dissipation (Figure 12).

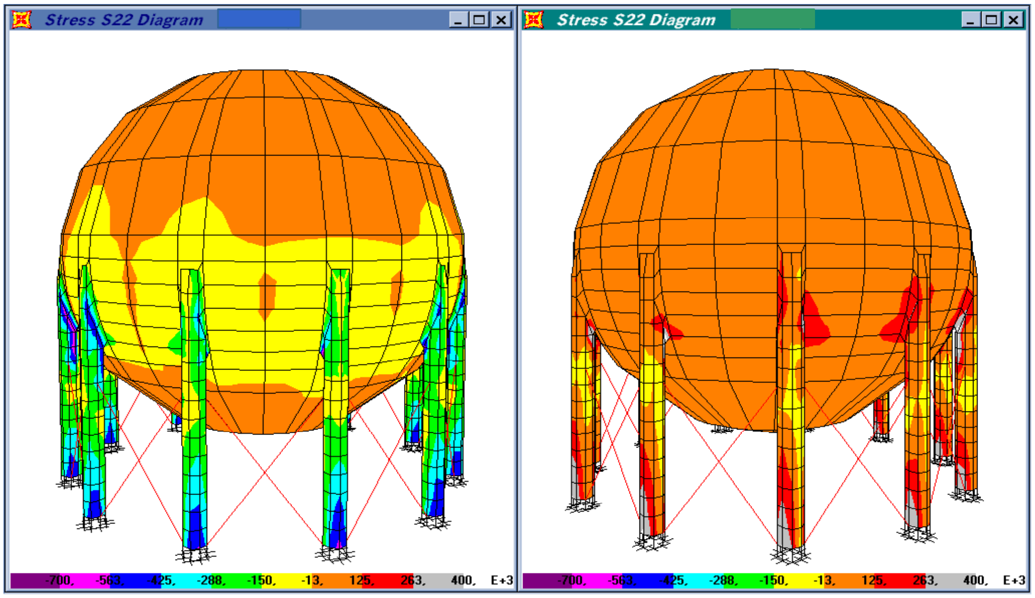

Figure 11: Max and min normal stress distribution in the un-protected tank

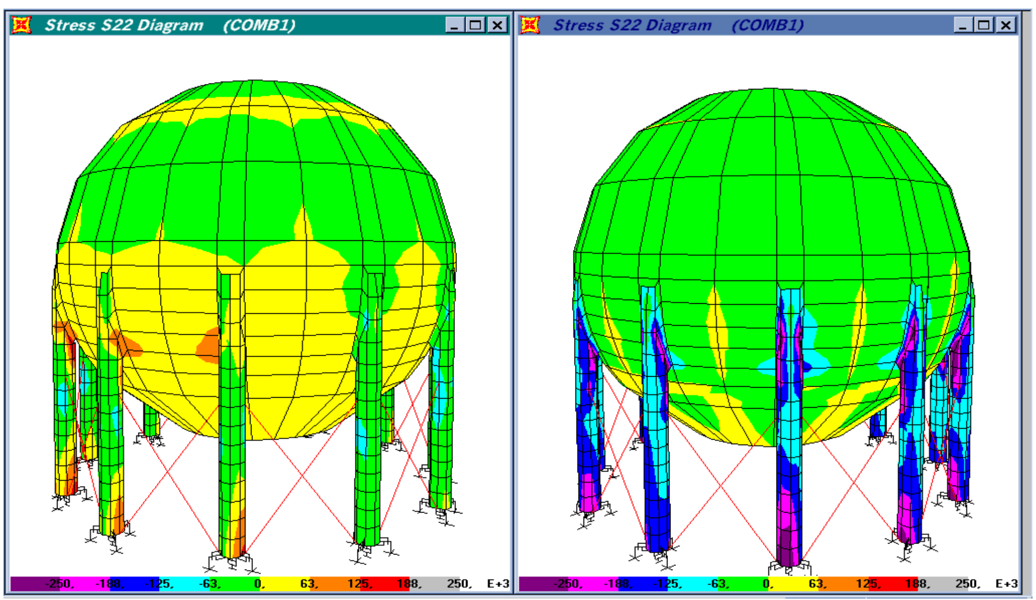

Figure 12: Max and min normal stress distribution (EPDs at the columns' base)

A NEW DISSIPATIVE BRACING SYSTEM

The development and validation of a new elastic-plastic dissipative bracing system, light, easy to move and install, particularly suitable to be inserted within framed structures is here reported, (for details see Renzi [11]). This uses elastic-plastic steel elements as energy dissipators, inserted in an Articulated Quadrilater, (AQ), to be connected by tendons within the inter-story space, or between columns.

An example arrangement of the AQ, by means of diagonal tendons, at the centre of a rectangular frame to which it is geometrically similar is shown in Figure 13. The energy dissipation occurs in "C" shaped steel devices, Ciampi [8], placed along the diagonals of the AQ, and hinged to its vertexes (see Figure 14).

For significant story drifts, large displacements of the system are obtained, and the kinematical behavior of the AQ tends to maintain all tendons in tension, with economical benefits for their sizing. In fact, while small drifts do not induce significant axial force due to the kinematical behavior of the AQ, for large displacements the diagonal which becomes shorter varies its length more than the other one, which elongates; as a consequence the entire bracing system is always stretched.
The AQ, designed to remain elastic, has the main function of activating the flexural elastic-plastic behavior of the "C" devices during the deformation of the AQ, while carrying the axial forces, and avoiding, consequently, possible negative effects of the plastic interaction between flexural and axial behavior in the devices.

The particular system used for validation has been designed for an existing 3D steel frame, 3.00 m long, 2.40 m wide and 4.00 m high. It is made of a couple of two-story, one bay, parallel frames, (Figure 13). The added masses, eight concrete blocks, (four at the first floor, four at the second), weigh 1200 kg each.

Figure 13: View of the test structure

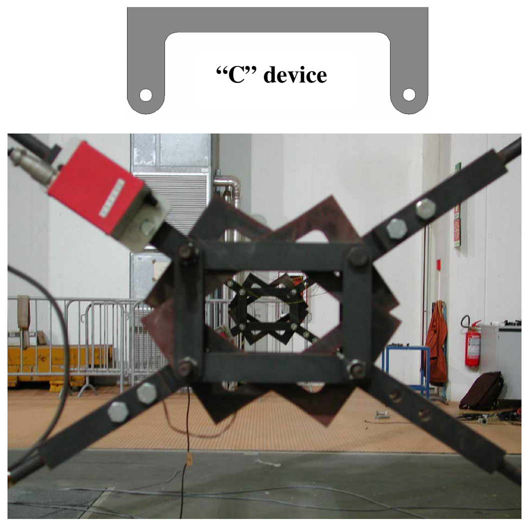

Figure 14: Detail of the AQ with four dissipators

The dynamical behaviour of the frame was already well known from previous tests, so it has been possible to use simple numerical models to analyze the effect of differently scaled AQ. To guarantee a small system it was decided to adopt a AQ whose dimensions, (170×260 mm), with respect to the frame, are in the scale 1:17. In this case, for a story drift equal to 30 mm (which corresponds to initiation of non linear behavior in the frame), the rate between the length variations in the diagonals, computed by a kinematical non linear analysis, is equal to 1.16. As regards the design of the "C" shaped devices, being well known the behaviour of the frame, (in terms of stiffness), it was assumed that the frame should remain elastic, in the controlled situation, up to a PGA 0.7g.

By using the methodology proposed in Ciampi [12] and by assuming that the yielding displacement of the devices equals 0.2 times the yielding displacement of the frame, the plastic force in the devices and the design of the single dissipators have been easily obtained.

The dynamical tests have been performed by using the 4x4 m 6DOF shaking table installed at the MAT-QUAL *Structural Dynamics and Vibrations Control Laboratories* of the ENEA Research Centre, Casaccia, near Rome (Italy).
The structure has been tested in different configurations, among which the most significant are:

NC – with braces and AQ installed, but without C-shaped devices;
C2 – with two devices in each quadrilateral at first and second story;
ND – un-braced configuration.

The results of over 100 seismic tests have been recorded and analyzed. Just as an example, the results obtained by using the “Sofita” input, an artificial accelerogram compatible with the elastic EC8 spectrum, are reported; in particular the performances of C2 and NC control configurations, in terms of peak values of first story drift and total base shear, for inputs at different nominal PGA, are compared with the corresponding results obtained for the unbraced configuration (ND). The ND results are linearly extrapolated, having been the corresponding tests stopped at PGA 0.20g, (nominal elastic limit of the un-braced frame).

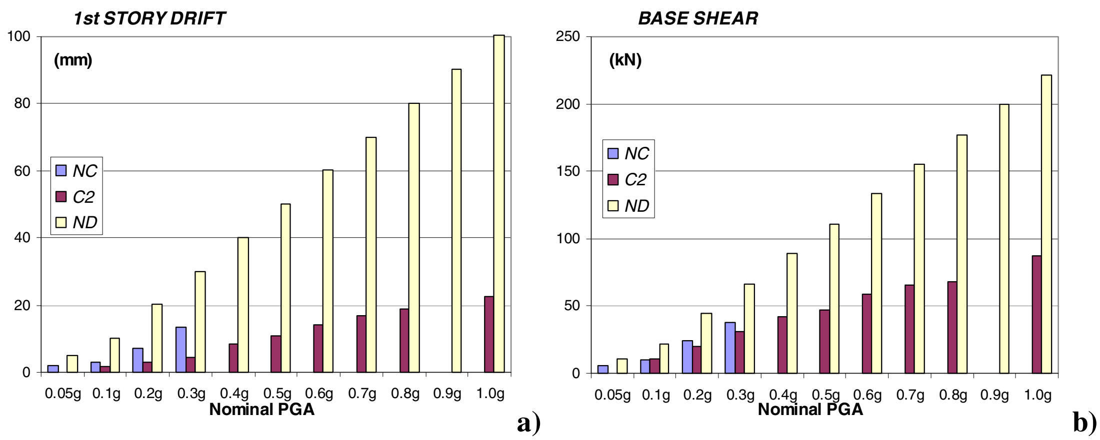

Figure 15: a) First story drift, b) Base shear for different nominal PGA – (Sofita)

The system appears to behave very satisfactorily, even at intensity levels different from the one used for the design (Figure 15). In particular, by comparing the C2 configuration with the un-braced frame (ND) configuration, the reduction of the maximum story drift is around 80% for every PGA, whereas the reductions of the base shear peak values are greater than 50% and reach even 60%, in correspondence with the design level of the control device (PGA = 0.7g).

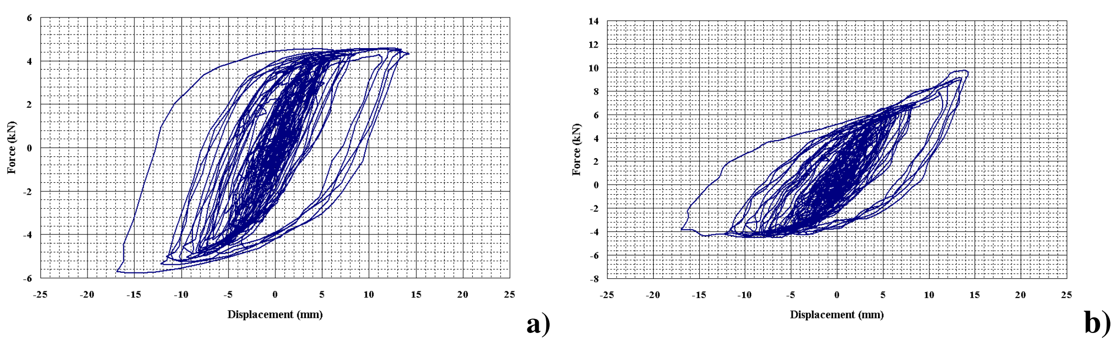

Figure 16: Force-displacement cycles; a) Dissipators, and b) Tendons

The experimental force-displacement cycles, for the dissipators (Figure 16a), show a very good behaviour without degradation, whereas for the tendons Figure 16b shows the hardening behaviour of the bracing system, due to the kinematical non-linear effect of the AQ.

CONCLUSIONS

The paper has presented the general approach and some results of a research activity, aimed at the evaluation of the benefits attainable by using passive control techniques for the seismic protection of critical equipment and components in industrial process plants.
The approach is based on a good comprehension of the particularities of the structures involved and of the consequences which might be caused by damage or collapse situations, and on the performance of significant numerical case-studies, supported by basic experimental and theoretical research activity on control techniques and devices.
The first results are very encouraging and induce to continuing along the presented research lines.

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