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DEVELOPMENT OF NEW BASE ISOLATION DEVICES FOR APPLICATION AT REFINERIES AND PETROCHEMICAL FACILITIES

Paul SUMMERS[1], Paul JACOB[2], Joaquin MARTI[3], Guilia BERGAMO[4], Luis DORFMANN[5], Gabriella CASTELLANO[6], Alessandro POGGIANTI[7], Dimitris KARABALIS[8], Heiko SILBE[9], and Stelios TRIANTAFILLOU[10]

SUMMARY

The concept of seismic isolation is not new, but it has not generally been used in heavy industrial settings. The European project, INDEPTH (Development of INnovative DEvices for Seismic Protection of PeTrocHemical Facilities), supported by the *Environment and Sustainable Development Programme* of the European Commission Research Directorate General (Contract EVG1-CT-2002-00065), has, as its objective, the development of new base isolation devices, suitable for application at refineries, LNG and petrochemical facilities beneath critical structures, such as cylindrical tanks and spheres.

The intent of isolation to reduce seismic risk and enhance performance reliability, especially for beyond design basis events, since many of these critical facilities are located in areas of high seismicity world-wide. In conjunction with development of isolation devices, new flexible piping joints will also be developed in order to accommodate increased displacements beneath isolated structures.

The project addresses the following: (1) selection of critical structures at two petrochemical facilities (Aspropyrgos Refinery, Greece and Huelva LNG Import Terminal, Spain); (2) design and manufacturing of the devices; (3) numerical analyses to confirm the expected dynamic behavior, including fluid-soil-structure-interaction; (4) experimental validation through shaking table tests of structural mock-ups both

[1] MMI Engineering, Warrington, UK, Email: psummers@mmiengineering.com
[2] MMI Engineering, Warrington, UK, Email: pjacob@mmiengineering.com
[3] Principia, Madrid, Spain, Email: marti@principia.es
[4] Enel.Hydro, Seriate, Italy, Email: giulia.bergamo@enel.it
[5] University of Applied Sciences, Vienna, Austria, Email: dorfmann@mail.boku.ac.at
[6] FIP Industriale, Padova, Italy, Email: castellano.fip@fip-group.it
[7] ENEA, Bologna, Italy, Email: poggiant@bologna.enea.it
[8] University of Patras, Patras, Greece, Email: karabali@upatras.gr
[9] IWKA BKT, Stutensee, Germany, Email: Heiko.Silbe@iwka-bkt.de
[10] Hellenic Petroleum, Aspropyrgos, Greece, Email: striantafillou@hellenic-petroleum.gr

with and without the device; and (5) quantification of technical/economical/safety benefits by comparison with the conventional state-of-the-art seismic design at industrial facilities.

At the time of the conference, the multi-year project will be approximately two-thirds completed (September 2002 – August 2005). The paper, however, will only describe the results and achievements of the first 12 to 18 months. In particular, two aspects will be discussed: the use of fiber-reinforced rubber bearings and the protection of spheres through energy dissipating braces and base isolation.

PROBLEM AND ITS SIGNIFICANCE

It is well known that some parts of Europe are in areas of high seismic risk, and within these areas there are numerous refineries and other petrochemical/industrial facilities.

The motivation for the project is to increase the seismic performance reliability of such facilities, both existing and future, in the face of high earthquake risk, through the development of new and innovative devices and techniques. Concern for society, quality of life of surrounding communities and impact on the environment, forces policy makers to assess the risk of hazardous material releases from refineries and petrochemical facilities during earthquakes. In fact, a major seismic event in an industrialized area could damage (and has damaged in the past) process equipment, storage facilities and transfer (or lifeline) systems. The start of fires and the release of airborne toxic gases and/or volatile liquids may obstruct post-earthquake rescue operations and can have major social and economic consequences. An example in case is the initiation of multiple fires at the Tupras Refinery and loss of production after the Izmit earthquake in Turkey [1, 2, 3, 4].

PROPOSED APPROACH

The approach of the project to the problem is manifested through the following main steps:

- Selection of critical structures from walkthroughs performed at the Aspropyrgos Refinery, Greece and the Huelva LNG Facility, Spain. Both are located in seismically active areas.
- Definition of site-specific and generic seismic hazards.
- Selection of main design parameters of the devices; design and manufacturing of the devices.
- Numerical analyses to confirm the design parameters versus the expected dynamic behavior of the devices, identification of specific fluid-soil-structure-interaction (FSSI) problems and experimental validation through shaking table tests.
- Quantification of technical/economical/safety benefits with respect to the conventional state-of-the-art measures presently adopted and potential application to retrofit of existing facilities.

The structures addressed by the project include LNG and critical product storage tanks (such as firewater tanks) and spherical storage vessels (often containing ammonia or LPG). For these structures, a solution (in terms of technical effectiveness and economic feasibility) capable of reducing the seismic vulnerability and enhancing the performance reliability is to be developed in this project. In particular, for each structure, a seismic isolation and/or energy dissipation system will be selected as an alternative (and an improvement) over the more traditional seismic design or retrofit concepts. The project objectives will be pursued by:

- Development of new concept seismic isolators and flexible joints for accompanying interconnected piping, taking into account the specific needs of tanks and spheres, recognized as some of the most critical components (for their potentially hazardous contents and by their inherent seismic vulnerability) in a petrochemical facility.

- Use of updated state-of-the-art analytical techniques to compute and measure the effects of FSSI on the seismic behavior of structures, in both their existing configuration and with the proposed new isolation/energy dissipating devices, subject to the appropriate performance requirements.

- Quantification of the technical and economic benefits of such devices, including consideration of the need for protection from fire and chemical attack due to the highly aggressive and corrosive operating environments.

- Preparation of guidelines for selection of proper isolation and/or energy dissipating devices.

The active participation of end-users in the formulation of the main objectives assures that the scientific/technological goals will be relevant to industry requirements and focus on problem-solving research.

THE SELECTED STRUCTURES

Three types of structures found in petrochemical facilities have been selected as examples for the application of isolation devices in this project:

- Above-grade LNG storage tanks.

- Above-grade cylindrical vertical storage tanks containing liquid product or firewater.

- Spheres containing pressurized (and possibly refrigerated) liquid product.

Each of these structures represents a different set of economic and technical challenges when applying base isolation devices.

Large LNG storage tanks of the order of 160,000 m3 volume are found in LNG export liquefaction and import regasification facilities (the latter being more relevant, in Europe, to risk of seismic hazards due to demand for gas). The LNG tank stores natural gas in a liquefied state at a temperature of -168°C, which represents a considerable quantity of stored chemical energy that would be released should a failure due to a seismic event result in the liquefied gas coming in contact with atmospheric oxygen, thereby posing significant risks to the surrounding population. LNG tanks are, for the most part, designed as above ground structures with concentric steel inner (containing the liquefied gas) and outer reinforced/prestressed concrete shells. Design of the tank to withstand seismic loads presents specific issues, particularly anchorage of the inner tank to the outer tank structure. At present, there are four sites with base-isolated LNG tanks. In all cases, the use of isolation units was relatively expensive and for various reasons had significant impact on construction schedules. The challenges therefore for applying base isolation to LNG tanks, within the INDEPTH project, are to develop economic isolator units that can be used for the expected range of tank sizes in Europe, that can be installed with minimum impact on construction schedule, and that can accommodate the unique variability of the mass of stored product (from full to near empty).

Conventional product storage (containing crude oil, refined products, benzene, or other aromatics) and firewater tanks, containing liquid up to over 100,000 m3 in volume, are the most common type of storage unit in petrochemical facilities. Containment of these products (harmfully to the environment and extremely flammable) during a seismic event is therefore desirable. Their typical construction costs are relatively low (unless anchorage is required) and consequently, base isolators would need to be economic to be viable. For anchored tanks, the cost of isolators can be offset against the cost to include anchorage in the design, and the cost of modifications to the tank foundation system. It is in this application that the INDEPTH project will focus on (economic) fibre-reinforced rubber bearing isolators.

Spheres containing liquid product under pressure also represent a significant hazard should a failure (and subsequent loss of product) occur. A typical sphere consists of a near spherical pressure vessel, supported on usually between eight and twelve legs with bracing to act as the primary lateral force resisting system of the structure. In addition to its variable mass, a key aspect of isolating spheres will be to ensure that there is minimal differential motion between the base of each leg. As with other structures, the economic inclusion of isolators will require the cost of the isolators and associated design modifications (including flexible piping and connections) to be offset by reductions in the design and construction costs of traditional spheres and a demonstrable reduction in seismic vulnerability during large earthquakes (and beyond design basis conditions).

Finally, a major challenge for designing isolator units for all three of the selected structures is that the mass of contained fluid can vary throughout operational life. Consequently, the base isolation units must also be able to cater for variable mass in their design. Further, the cost of using isolation will need to include any additional cost in providing flexibility in the piping and other connections that span between the structures and the first adjacent fixed pipe support or other point of fixity (such as a containment wall through which the piping penetrates).

Six specific candidate structures have been selected based on a review of the Huelva and Aspropyrgos facilities for the analysis:

- Two LNG storage tanks (Figures 1 and 2) with the following main characteristics: capacity 60,000 m^3 and 100,000 m^3; outer tank diameter, 49.4 m and 67 m; and aspect ratio (height/diameter), 0.81 and 0.56.

Figure 1: Huelva LNG Plant: 60000m^3 **Figure 2: Huelva LNG Plant 100000m^3** **Figure 3: Tank P8803**

- Three liquid storage tanks (Figures 3, 4 and 5) with the following main characteristics, which cover a quite wide range of different types of contents and aspect ratios. (Note that T729 was not in Aspropyrgos, but in another site, inspected before the start of the project):

Tank Identifier Code	P8803	P5151	T729
Contents	ATM Residue	Demin Water	Lube Oil
Capacity (m^3)	67600	8557	755
Mean Diameter (m)	66.44	24.4	8.24
Aspect Ratio	0.29	0.75	1.75

Figure 4: Tank P5151

Figure 5: Tank T729

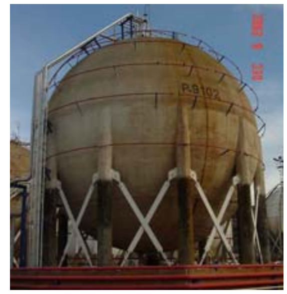

Figure 6: Sphere P9102

- One spherical tank, P9102 (Figure 6), containing refrigerated polypropylene with the following main characteristics: capacity 4,200 m3; sphere diameter, 19.6 m, and number of supporting columns, 11.

THE SEISMIC HAZARD

Amongst the potential earthquake hazards (the seismic hazard) that may affect the structures, equipment and piping at a petrochemical facility, strong ground shaking is responsible for the most serious and widespread damage, since other hazards (ground failure caused by the rupture of a fault and by liquefaction and/or landslides and coastal inundation caused by seiches, tsunamis or tidal waves) are normally guarded against by careful site selection.

For most petrochemical facilities, evaluation of the seismic hazard is governed by codes, standards (national and international) and design norms that are relevant to location of a specific facility, requiring seismic loads to be considered for a single event, prescribed by the probability of a given earthquake occurring within a specific time period. An exception to this is seismic design at LNG facilities, where a dual criteria approach is mandated [5, 6]:

- The Operating Basis Earthquake (OBE), intended to guarantee continued operation (or limited downtime/economic loss) at a lower level event. Elastic or near-elastic design rules are used and the return period adopted is 475 years, corresponding to a 10% probability of exceedance in a lifetime of 50 years.

- The Safe Shutdown Earthquake (SSE), intended to afford the general public and environment a level of safety should an extreme earthquake occur. Design rules are fully non-linear, a complete loss of function, even permanent, is allowable (except major collapses or major releases of hazardous materials) and the return period is 10,000 years (reduced to 5,000 years by the latest version of NFPA 59A).

The seismic hazard is generally evaluated using a probabilistic approach, taking into account activity rates, existing geological and tectonic data and attenuation laws in order to calculate the effects at the site. Several approaches exists from the traditional procedure described in [7] to the more innovative outlined in [8] and [9], used also to define the seismic hazard at a number of LNG facilities [10]. For calculation purposes the seismic hazard is defined using response spectra or artificial time histories generated from response spectra.

In the development of the INDEPTH project, specific seismic hazard assessments are available to perform accurate analyses for the tanks identified as candidate structures at the two reference sites (the Huelva LNG plant in Spain and the Aspropyrgos Refinery in Greece). Nevertheless, as many investigations have to be carried out in a generic fashion in order that the results might be applicable to other locations in Europe and, indeed, elsewhere in the world, a generic description of the hazard at a site, in terms of spectral shape and reference peak ground acceleration, has been adopted, allowing studying the acceleration levels at which the various design solutions are determined to be unfeasible, attractive, required, etc. The spectral shapes (as SB, SC and SD) adopted, see Figure 7, are those that EC8-draft [11] recommends for Soil Types B, C and D and Type 1 earthquakes (Magnitude Ms>5.5) and S=1. The spectral shape for the vertical motion can be obtained by multiplying by 0.7 the shape obtained for the horizontal motion. The reference acceleration a_g will be taken as a continuously varying parameter, descriptive of the hazard level at the site.

Finally, since some analyses are to be carried out in the time domain, two accelerograms have been generated for each of the three spectral shapes adopted: one having a duration of 20 s, and the second one a duration of 40 s. An example of these accelerograms is presented in Figure 8 together with the corresponding spectra. The accelerograms will be scaled up and down, in proportion with the reference peak ground acceleration, in order to avoid introducing additional variables in the generic analyses.

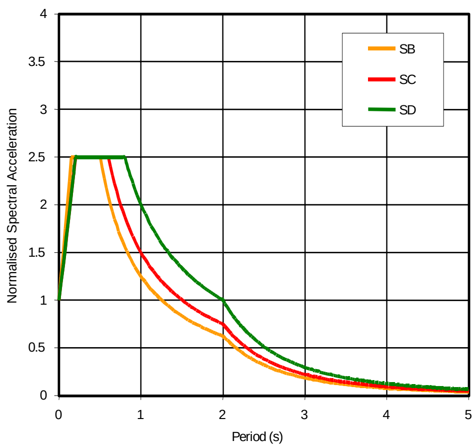

Figure 7: Recommended Spectral Shapes in Terms of Period

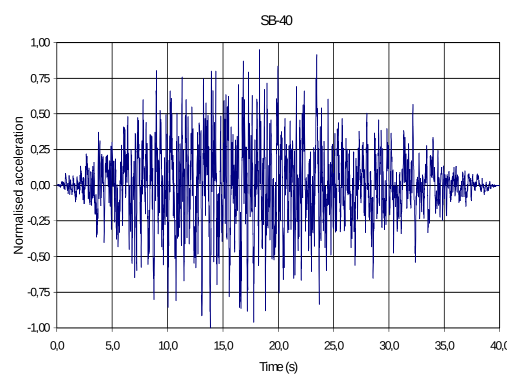

Figure 8: Normalized Acceleration Time History (Soil Type B, 40 Seconds)

THE NUMERICAL ANALYSES

The numerical analyses are in progress, to support the development of the new isolation devices. The analyses take into account different topics, such as the non-linear behavior of isolation devices, the effects of sloshing motion at different filling levels, the soil-structure interaction and the fluid-structure interaction. They are developed with different levels of complexity, starting from simple classical Housner models to the most sophisticated codes, in order to supply design procedures tuned on the candidate structures chosen. As an example, the following sketch (Figure 9) illustrates the effect of sloshing of the contents inside the P5151 tank.

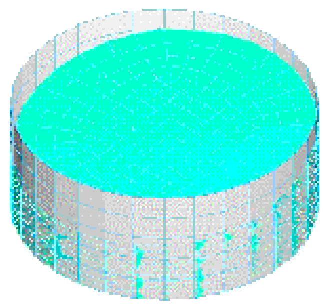

Figure 9: Fluid Sloshing Model, Tank P5151

SEISMIC PROTECTION OF SPHERES THROUGH DISSIPATIVE BRACES AND/OR BASE ISOLATION

For the seismic protection of spheres the use of both base isolation and dissipative braces has been considered. Parametric analyses are being carried out with both linear and nonlinear base isolation systems, e.g., high damping rubber bearings, lead rubber bearings, sliding bearings with steel hysteretic elements (Hitec [12], Castellano [13]), combination of rubber bearings and sliding bearings, etc, to find the optimum system on a cost-benefit basis. A series of parametric analyses have also been carried out, in order to optimize the design of dissipative braces and select the most effective type. Two types of damping technologies have been considered, both very reliable: non-linear fluid viscous dampers (Castellano [14]), and steel hysteretic braces.

In this section, we describe the optimization study of dissipative braces, in particular steel hysteretic braces, and then compare the results of the sphere protected with the optimized dissipative braces with those of the sphere isolated with high damping rubber bearings of two different types, as well as with the unprotected tank (i.e., in the original configuration, fixed base, with conventional tension-only braces).

The FE model used in these numerical analyses was implemented in the ABAQUS code. The model includes the eleven columns modelled with beam elements; the conventional braces are modelled with nonlinear springs to take into account the compression buckling. The sphere and the fluid are simply considered masses rigidly connected to the top of the columns. The steel hysteretic braces are modelled with elastic-plastic beam elements. The isolators are modelled coupling in parallel a spring with the same stiffness and a linear dashpot providing the damping. The methodology was a step by step analysis in all the cases to take into account the nonlinear behavior of the bracing system. All the analyses were performed with the tank 100% filled.

The EC-8 design spectra [11] for three different soil types, i.e., Type B, C, and D, have been taken as reference spectra for this study. However, for the sake of simplicity, only the results for soil Type C are reported here. The input for the dynamic analyses were artificial time-histories, with duration of 20 s, matching said spectra. A peak ground acceleration (PGA) of 0.4 g has been considered for the protected structures; conversely, analyses on the unprotected tank were carried out with a PGA of 0.098 g, i.e., the highest PGA value that guarantees that the sphere remains elastic.

Steel hysteretic braces can be realized using a variety of devices based on yielding of metals by bending (e.g., tapered pin, triangular, butterfly or crescent moon elements) or by torsion [12, 13, 15, 16], combined with conventional steel braces in different configurations (X, K, etc.). However, here the focus is on buckling-restrained braces (BRB). These are steel hysteretic braces that yield in compression/tension, in which Euler buckling in compression is restrained. A variety of BRBs having different restraining systems have been proposed and studied extensively [17], and in last ten years applied in almost 300 buildings first in Japan and subsequently in the United States. The most used restraining system, also selected for this study, consists of encasing a steel core, covered by a slip interface, into an outer steel tube filled with mortar. The core is designed to yield, at least for a portion of its length, and thus dissipate energy. This system not only prevents the core from buckling, but guarantees a stable hysteretic behaviour under cycling [18]. The stabilized hysteretic force vs. displacement law of the BRB has been modelled as bilinear. The following parameters of the bilinear curve have been varied, to find the optimum design for BRBs: the yielding force F_y, the elastic stiffness K_{el}, and the ratio of the post-elastic to elastic stiffness. Structural response parameters considered for the optimization were the acceleration at the centre of gravity of the sphere and the ratio of the energy dissipated by the BRB, E_d, to the total input energy E_i.

Preliminary results showed that the structural response is not very sensitive to the ratio of the post-elastic to elastic stiffness, varied in the range 0.015 to 0.035; thus, for most analyses it has been fixed and taken equal to 0.015, i.e., the value giving, as expected, optimum response. However, this low sensitivity allows the engineer to optimize BRB design without being bound by this ratio that is actually dependent on other design parameters. Conversely, the response is very sensitive to both the yielding force and the elastic stiffness. In general, the higher the elastic stiffness, the better the response, though at high values of elastic stiffness, further increase does not improve a lot the response; furthermore, the optimum yielding force depends strongly on the elastic stiffness.

Figure 10 shows an example of the parametric curves obtained from these analyses. It is important to note that in this case the minimum of the acceleration and the maximum of the energy ratio E_d/E_i is reached for the same BRB's design, but it is not the same in all cases. Consequently, in some case the optimization should be based on a compromise between different response parameters, or on a selection of the most important response parameter.

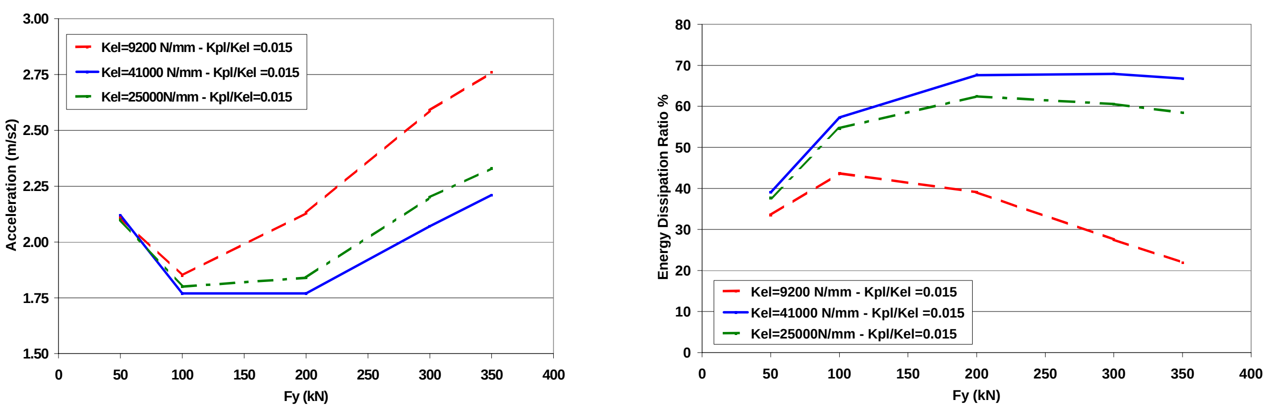

Figure 10: Optimization graph for BRB: acceleration (left) and energy dissipation ratio E_d/E_i (right) vs. yielding force of BRBs

The results shown in Figure 11 have been obtained considering for each value of yielding force the maximum elastic stiffness that can be realized with a cost-effective design of BRBs. In this case the minimum acceleration does not coincide with the maximum energy dissipation ratio; however, the optimum BRB in terms of acceleration (F_y=200 kN, K_{el}=37 kN/mm) is also the more cost-effective, and provides an energy dissipation ratio higher than 85 %, thus is selected as the optimum design. Results also show that the maximum displacement in the braces is not very sensitive to the change of elastic stiffness and yielding force. For the case selected as optimum it is about 55 mm.

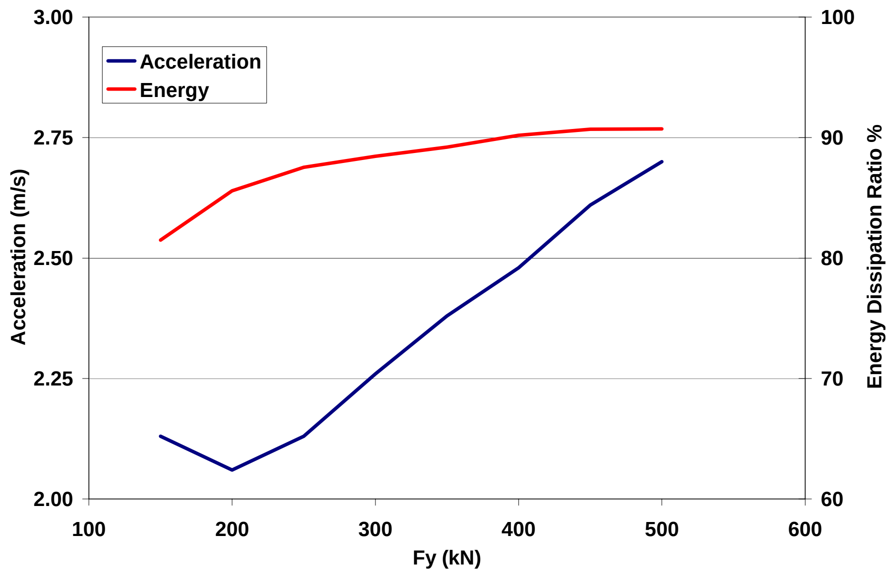

Figure 12: Optimization graph for BRB

As stated above, the seismic response of the structure with BRB, optimized as above, has been compared to that of the base isolated sphere (BI). Two BI configuration have been considered, corresponding respectively to a fundamental period of 2.03 s and 2.87 s. Each of the 11 isolators, in both cases high damping rubber bearings with 10 % equivalent viscous damping, has a horizontal stiffness of 2.36 kN/mm and 1.18 kN/mm, respectively, and was designed for a displacement of 300 mm (taking into account an increased reliability magnification factor of 1.2 according to EC8 [5]. Figure 12 reports this comparison in terms of amplification of the acceleration (i.e., ratio of the acceleration at the gravity center of the sphere to the PGA). It can be observed that the acceleration at the gravity center of the sphere is much lower than PGA not only in case of BI, but even for the sphere with BRBs. Actually, the latter provides an acceleration 16 % lower than the BI structure with T=2.03 s. If compared with the amplification of the acceleration in the unprotected sphere, that is 3.7 times higher than PGA (at PGA=0.098g), this shows the effectiveness of all the protection systems considered.

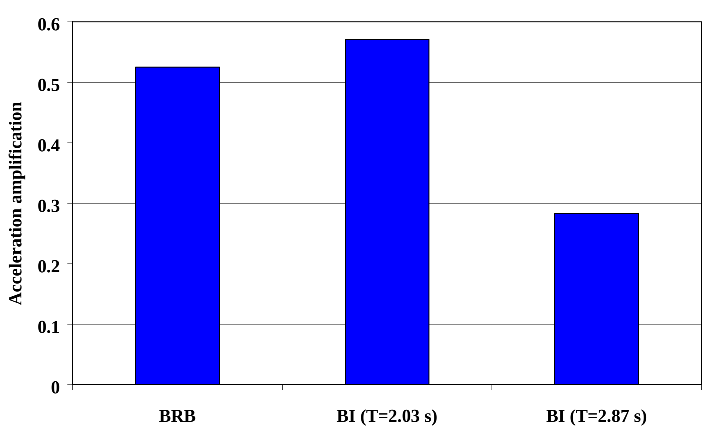

Figure 12: Ratio of acceleration at sphere's center of gravity to the PGA (=0.4g), for the protected sphere

A further comparison between the sphere BRBs and BI is given in Figures 13 and 14, in terms of time-histories of acceleration and energy. It is evident that both systems respond with a quite low frequency, thus explaining the strong reduction of acceleration in the structure. The input energy is higher for the sphere with BRBs, but most of it is dissipated through yielding by the BRBs, thus just a portion of it goes in the structural elements.

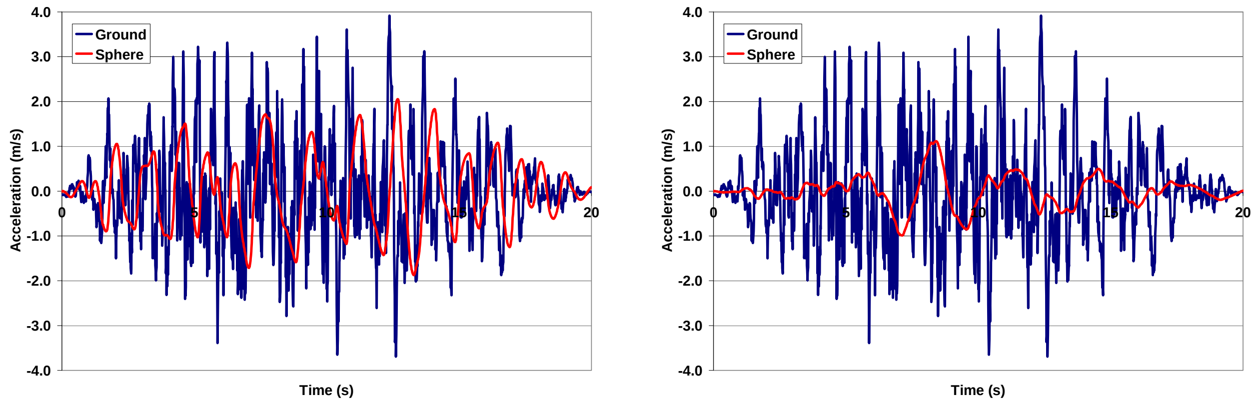

Figure 13: Time-histories of acceleration at the gravity center of the sphere and at the ground, for the spherical tank protected with BRBs (left) and with BI at T=2.87 s (right)

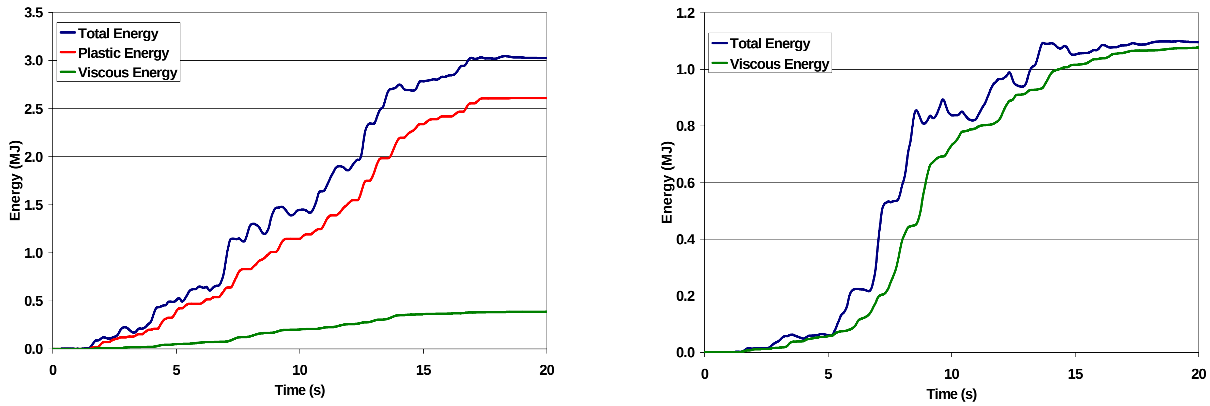

Figure 14: Time-histories of energy, for the spherical tank protected with BRBs (left) and with BI at T=2.87 s (right)

Figure 15 compares the response of the protected tank with that of the unprotected tank. As noted above, the calculations are not at the same PGA, because the limiting PGA of the unprotected tank (corresponding to significant damage, incipient failure of the braces, and potential collapse) is about 0.25 g, i.e., much lower than the reference PGA used for the calculations of the protected tank (0.4 g). Thus, for the purpose of comparison, the results for unprotected structure reported in Figure 15 as reference values are those at PGA=0.098 g, i.e., when the structure is still undamaged. It can be observed that all the passive protection systems herein considered give a structural response much lower than that of the unprotected structure, despite the PGA being more than four times higher. In particular, the sphere with BRBs has a response at least 65 % lower, and that base shear and overturning moment of the most flexible BI sphere (T=2.87 s) are only 31 % . These results allow one to conclude that optimized passive protection systems may avoid damage to the sphere even with an earthquake more than four times higher than the maximum one that would permit the unprotected structure to remain undamaged. Even the substitution of existing conventional braces with dissipative braces, deemed simpler and less expensive than the insertion of isolators for retrofit of an existing structure, would not only significantly increase the seismic resistance of the structure, but also avoid damage, thus allowing for functionality after a strong earthquake.

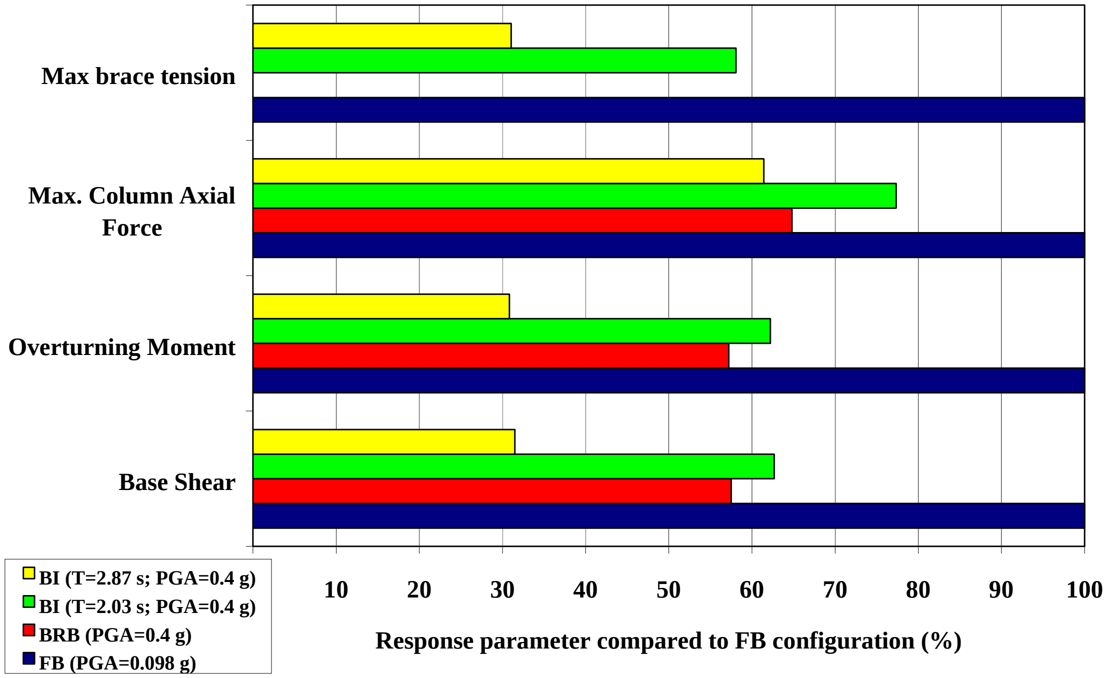

Figure 15: Comparison amongst protected (with buckling restrained braces – BRB or base isolation – BI) and unprotected (fixed base - FB) spherical tank.

FIBER-REINFORCED ELASTOMERIC BEARINGS

Seismic isolation methods frequently use reinforced elastomeric bearings to provide increased safety during earthquakes. Manufacturing involves vulcanization bonding of sheets of rubber to thin steel reinforcing plates to produce a composite with very high vertical and low in-plane stiffness. Present applications of these isolators, which are in general expensive and heavy, are often restricted to the protection of critical facilities, such as command centers, computer facilities, hospitals, landmark and historic structures.

Manufacturing of isolators is expensive since each one of them is built on an individual basis and no automation process is available to reduce costs. The high cost results from the labor involved in preparing the steel plates and laying up of rubber sheets and steel plates for vulcanization bonding in a mold. The steel need to be cut, sand-blasted, acid cleaned, and then coated with bonding compound. Next, the compounded rubber sheets with the interleaved steel plates are put into a mold and heated under pressure for several hours to complete the manufacturing process. On the other hand, the high cost of transportation and installation is attributed to the large weight of isolators, which easily can reach one ton and more for each single device.

The innovation proposed is to replace all steel reinforcement layers in the isolators with high-strength fibers in order to: reduce the weight of isolator; reduce the manufacturing costs; reduce the transportation costs; reduce the installation costs; and increase flexibility in design concepts.

The weight reduction is possible as reinforcing fibers are available with an elastic stiffness that is of the same order as steel. Thus, the reinforcement needed to provide the vertical stiffness may be obtained entirely from lightweight fibers in place of the traditional steel plates. The manufacturing costs can be reduced substantially since the process involving fiber-reinforced composites is less labor and time intensive and an automation process can easily be implemented, e.g., replace current approach of vulcanization bonding by microwave heating in an autoclave. Another benefit is the possibility to manufacture large rectangular fiber-reinforced composite blocks from which individual isolators could be simply cut from. In other words, the production of isolators would shift from a very expensive, individualized process to a highly cost effective method.

The first prototype bearings reinforced entirely with carbon fibers have been tested and evaluated for use as a seismic isolation ring around the perimeter of liquid storage tanks. The design details of the bearing are a fabric layer near top and bottom surfaces and five internal reinforcing layers. The rubber used for fabrication was a high damping natural rubber compound with the following dynamic shear properties:

Shear Modulus	0.4 MPa
Damping	11 %
Test Strain Amplitude	±100%
Test Frequency	0.5 Hz

Table 1: Dynamic shear properties for high damping natural rubber compound

The data shown below characterize a bearing with a rectangular shape with dimensions of 160 mm x 157 mm x 50 mm. Figure 16 shows the response to an applied vertical load. It is anticipated that the vertical stiffness be increased with an increasing amount of carbon fibers for each layer. Subsequently a number of shear tests were performed under load and displacement control. Shear tests indicated by numbers 1, 2 and 3 in Table 2 are performed under a constant vertical load of 80 kN. Tests 4, 5 are performed under displacement control. The vertical displacement reported for each test in Table 2 indicates that the current design is subjected to a large amount of creep, i.e., the amount of fibers need to be increased.

Figure 16 shows the response of the fiber-reinforced bearing subjected to vertical load. It may be observed that the vertical stiffness is lower compared to bearings reinforced by steel layers. The reason for this reduction is due to the limited amount of fibers used in each layer. Figure 17 represents typical experimental data when the bearing is subject to shear.

Test #	Vert. Displ. [mm]	Vert. Load [kN]	Comments
	8.51	80	Vertical Compression to reach 80 kN
1	8.8	80	Test 1: ± 2.5 mm @ 0.05 Hz, 4 Cycles
2	10.18	80	Test 2: ± 5 mm @ 0.05 Hz, 4 Cycles (80 sec)
3	10.72	80	Test 3: ± 10 mm @ 0.05 Hz, 4 Cycles (80 sec)
4	11.25	40	Test 4: ± 10 mm @ 0.05 Hz, 4 Cycles (80 sec)
5	11.25	45	Test 5: ± 20 mm @ 0.05 Hz, 4 Cycles (80 sec)
6	11.25	45	Test 6: ± 50 mm @ 0.05 Hz, 4 Cycles (80 sec)

Table 2: Test sequence of shear tests.

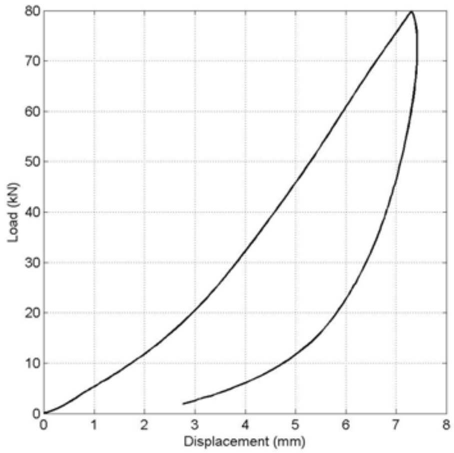

Figure 16: Vertical Load Versus Vertical Displacement Response of a Carbon Fiber Reinforced Bearing

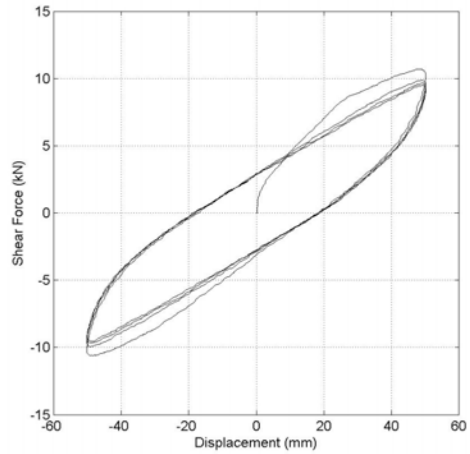

Figure 17: Cyclic Shear Test to ± 50 mm with Constant Vertical Load of 45 kN

THE EXPERIMENTAL VALIDATION

The experimental validation will explore a shaking table testing phase particularly focused on experimental verification of the effectiveness of the assembly "devices, with mock-ups". The experimental equipment, owned by one of the partners (Enel.Hydro/ISMES), is a 4 m × 4 m triaxial shaking table (Figure 18), able to test up to 300 kN specimens, with a maximum overturning moment up to 300 kNm, with 5 g's of maximum peak acceleration in horizontal/vertical directions and ±100 mm displacement.

Figure 18: The 6-DOF MASTER Shaking Table at Enel.Hydro/ISMES Premises (Seriate, BG, Italy)

Two physical mock-ups are envisaged:

- Cylindrical mock up in a geometrical scale of approximately 1:8.
- Spherical mock up in a geometrical scale of approximately 1:7.

Currently, the design of the mock-ups is in progress. The mock-ups will be tested both with and without the isolation devices, with different levels of fluid inside, by measuring accelerations, displacements and strains with appropriate sensors. Testing procedures will be developed for each pair mock-up/isolation device, completed where necessary through reduced-scale demonstrators of seismic expansion joints. Each device will be characterized as a single item through static and dynamic tests.

The aim is to experimentally assess the behavior of the devices and to tune the numerical models which are under development in the framework of the project. The effectiveness of the systems will be checked through characterization tests (sine sweep on the shaking table) and through seismic tests with the time histories. The measurements performed during the shaking table tests will be processed, giving the modal parameters of the mock-ups, the transfer functions of the items, their time responses with respect to the seismic base excitations. This information will be used to extend the findings to the full-scale structures and to suggest potential retrofits, if necessary.

THE EXPECTED ACHIEVEMENTS

The expected results and products of the project include development of full scale demonstrators of the devices, an integrated procedure for solving FSSI problems, assessment of the benefits compared to the conventional retrofitting techniques and design guidelines. In fact, considering that the devices to be developed are completely new, their use in a petrochemical environment will have to be strongly supported by a quantification of the technical and economical benefits, comparing them with the conventional state-of-the art measures presently adopted in such plants, focusing as well on the aspect of retrofitting, either through conventional methods or with the developed devices. Particular emphasis will be devoted to the safety issue, quantifying this increase with respect to the conventional methods. A specific task of the project is devoted to this topic.

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