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EXPERIMENTAL VERIFICATIONS OF SEISMIC PROTECTION OF STEEL AND R.C. STRUCTURES AT ENEA-CASACCIA SHAKING TABLES

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SUMMARY

This paper illustrates three experimental campaigns, carried out in 2002-2003, on the shaking table of the ENEA MAT-QUAL laboratories at Research Center Casaccia. The experiments have been carried on on large-scale steel and reinforced concrete structural models, seismically protected by means of several base isolation systems (steel-PTFE sliding devices, elastomeric, steel and Shape Memory Alloys isolators) and bracing systems (based on dissipative steel elements, arranged in traditional and innovative way, on Shape Memory Alloys re-centering elements and on electro-inductive dissipative devices). The results of these tests confirm, with experimental evidences, the performances and full applicability of these seismic protection technologies even for existing structures. A floor acceleration index has been proposed in order to evaluate comfort and serviceability conditions for strategic buildings.

INTRODUCTION

The new technologies for seismic protection of buildings, in particular seismic isolation and energy dissipation, has received greater attention and interest not only from the experts in the field, by now certain of their knowledge, but also after the calamitous events that periodically strike the territory, from public opinion and competent authorities. The awareness of the existence of such methods and technology is widespread; these methods allow to survive to earthquakes and, above all, allow to live with them, with enormous technical, scientific, social and economic consequences. Such awareness must now be supported by the transfer of the results achieved in the research to actual full-scale realizations. On the other hand, it is evident that only dynamic experimental testing on large scale structural models allows the full application of such researches and simultaneously transmits, with experimental evidences, the awareness of the effectiveness of such methods to all operators, administrators and political planners.

ENEA (Italian agency for new technologies, energy and environment) has been committed to the study and experimentation of various innovative techniques for seismic protection of structures, establishing

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important and fruitful collaborations with public research institutions, such as various universities (e.g. University of Rome “La Sapienza” and University of Basilicata), the Italian Government Department for Civil Protection (office for the National Seismic Survey), and various industrial companies. The main point of such researches hinges on experimental tests that make use of the important shaking table systems installed at the MAT-QUAL laboratory of Structural Dynamics and Control of Vibrations of the ENEA-Casaccia Research Center. This activity has led to significant experimental confirmations of the effectiveness of such techniques.

As previously mentioned, among seismic protection techniques certainly the most mature and ready for true application are those founded on base isolation and on the additional energy dissipation. The technologies and the materials that can be used for the realization of these protection techniques and the structural configurations to be protected are varied. The present paper illustrates several experiments on shaking tables, carried out in 2002 and 2003 in the ENEA-Casaccia laboratories, on large scale structural models in steel and in reinforced concrete, seismically protected by means of base isolation systems and bracing systems. In particular will be illustrated experimental campaigns performed, in several structural configurations, by using isolation systems, founded on the use of rubber and steel devices, steel-PTFE sliding devices, U-shaped steel isolators, SMA (Shape Memory Alloys) isolators, and bracing systems founded on the use of dissipative steel dissipative devices (arranged in various ways), electro-inductive dissipative devices and re-centering SMA devices.

After a brief description of the equipment used in the tests, the tests and the their main results will be briefly described, in order to underline the effectiveness of the protection technology experimented.

THE SHAKING TABLES OF THE ENEA CASACCIA R.C.

The principal instruments for seismic tests in the MAT-QUAL laboratories of the C.R. ENEA-Casaccia, are composed of two 6 degrees-of-freedom shaking tables with digital control (Figure 1). The most important characteristics of the tables are illustrated in Table 1.

Figure 1. The shaking tables at ENEA MAT-QUAL laboratory

The seismic tests illustrated in this paper have been carried out on the largest table (system 1), controlled by MTS software 469D Digital Seismic controller and STEX MTS 3.0 (Seismic Execution test); the data acquisition has been effected by the MTS system 469D. This equipment has also been used in the past for other experimentations on passive structural control systems applied, e.g., on civil, Ciampi [1], and industrial, De Canio [2] Cimellaro [3] structures, and also for the seismic protection of structural elements in historical monumental cultural heritage, De Canio [4].

Table 1. Main characteristics of the shaking table systems

	System 1	System 2
Dimensions (m)	4 × 4	2 × 2
Degrees of Freedom	6	6
Frequency Range (Hz)	0 ÷ 50	0 ÷ 100
Acceleration (0-peak)	3 g	5 g
Velocity (0-peak)	0.5 m/s	1.0 m/s
Displacement (peak-peak)	0.25 m	0.30 m
Max. Overturning Moment	≈ 300 kNm (*)	≈ 30 kNm

(*): e.g. 3g PGA for a 10 tons rigid mass at 1m height

SEISMIC TESTS ON A STEEL STRUCTURE PROTECTED BY ELECTRO-INDUCTIVE DEVICES

Within a collaboration which has involved sections MAT-QUAL and PROT-PREV of ENEA and the industrial partner ALGA, in March 2002 a campaign of seismic tests on a steel model structure, controlled with braces connected to the structure by means of electro-inductive devices for structural control DECS, has been realized, see also Renzi [5]. Such devices are based on the forces developed in metallic elements moving into a magnetic field. In this specific application DECS behave as passive devices because the magnetic field is constant and produced by permanent magnets.

The test structure, called MISS (Figure 2), is a four-storey steel structure composed by 6 vertical columns (HE 100 B) 4.5 m high, bolted on a base frame. Four horizontal frames (HE 100 B) can be bolted at the columns, with an inter-storey distance of 0.9 m. Each horizontal frame, which is 3.3 m x 2.1 m, can support up to 8 reinforced concrete masses, each weighting 12.8 kN. The total mass of the structure, with the additional masses used in the tests, is about 23 tons. In this application, MISS has been equipped with 4 DECS, connected to the frame and to 4 additional rigid braces, Figure 2.

For the response acquisition the following transducers have been installed on the structure: 7 seismic accelerometers on the table and on the frame levels; 5 laser displacement transducers in order to measure the floor absolute displacements and the DECS deformations; 8 strain gauges in order to measure the brace deformations. The seismic test was performed in the following configurations: NC without control device (unbraced structure); RC with rigid connection between the frame and braces; DECS with electro-inductive control device installed. The mono-directional seismic inputs was two synthetic accelerograms, compatible with B and C soil spectra of EC8 (BGS and CGS input respectively), CEN [6], and a record of the 1976 Friuli earthquake (Tolmezzo, Italy). The PGA (Peak Ground Acceleration) for the three non-scaled accelerograms are equal to 0.30, 0.31 and 0.35g. respectively. Starting from low intensity, for example −12db, every input was repeated with increasing intensity until reaching the maximum allowable value of the inter-story drift (20 mm: elastic limit of the structure).

Figure 2. MISS installed on the shaking table and detail of the DECS device

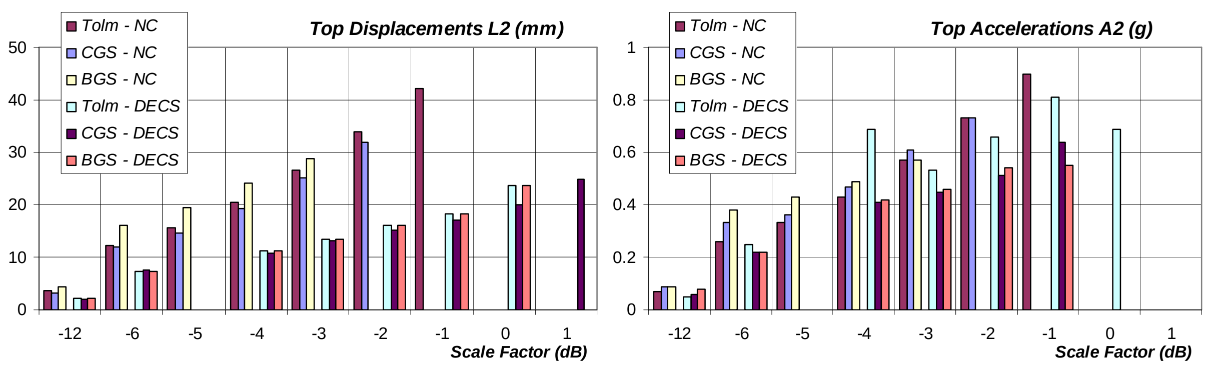


Figure 3. Maximum top displacements and accelerations, NC and DECS configurations

These tests have shown the good performances of the proposed control system. In fact, it was possible to submit the unbraced structure (NC configuration) by a measured excitation with a PGA of 0.34g and 0.24g, respectively for the natural accelerogram and for the synthetic accelerogram, while the model with devices installed (DECS configuration) reached 0.38g for Tolmezzo record and also 0.50g of PGA for CGS and BGS. In Figure 3, a comparison of the results is reported in terms of maximum top displacements and accelerations. This comparison underlines, with respect to the NC configuration, the reduction of the displacement obtained, without increasing the accelerations, in DECS configuration. The observation of the time histories underlines that such reductions are verified not only for the peak value, but also for all time history. More details concerning this experimentation may be found in Renzi [5].

SEISMIC TESTS ON A R.C. BUILDING PROTECTED BY MEANS OF VARIOUS BASE ISOLATION AND DISSIPATIVE BRACING SYSTEMS

The second experimental campaign illustrated in this paper was carried out within a convention (SICURO project) between ENEA, the Italian department of civil protection (office for the National Seismic Survey), the Dept. of Structures Geotechnical and Applied Geology (DiSGG) of the University of Basilicata and the industrial partner TIS. The purpose of this convention was the shaking table experimental validation of seismic protection systems of structures, by using various typologies of base isolation systems and dissipative brace systems.

Three identical reinforced concrete models, of three storey, 1:4 scaled and with a total mass of about 10 tons, have been realized. The structures were infilled with a masonry tamponage not able to resist a seismic event. The first test session, performed on model n.1, had the purpose of comparing the performances of the several passive systems for seismic protection. This experimentation constituted the prelude to the second session of the convention, characterized by the repetition of the more meaningful tests on building n.3 during the public test day *"La sicurezza sismica degli edifici esistenti e le nuove tecnologie per il loro adeguamento"*, organized with wide success on the 21th March 2003 in the ENEA-CASACCIA R.C. This experimentation was completed and integrated with the tests on the model n.2, the results of these tests, carried out in February 2003, within the TREMA project founded by the Italian Minister for Scientific Research, confirm their repeatability.

The model used for the experimentation is a 1:4 scaled model of a prototype building in reinforced concrete for civil residence, of usual dimensions (height of 3 m for each level, and spans of about 5.30 m) designed in accordance with the Italian seismic rules previous to 1971. This structure can withstand only the vertical load. The r.c. frame of the model was infilled with elements in masonry and on each floor additional steel masses were installed (for about 2.4 tons for level).

The first test session, carried out in September and October of 2002, involved the following structural configurations:

1. Rubber Isolators (IG): Base Isolation with elastomeric devices;
2. Steel Isolator (IA): Base Isolation with U-shaped steel dissipative devices;
3. SMA Isolator (ISMA): Base Isolation with re-centering Shape Memory Alloys devices ;
4. Fixed base (BF): model fixed to the table without seismic isolation.
5. SMA Braces (ContSMA): Braces with dissipative elements and re-centering SMA devices;
6. Steel Braces (ContAcc): Braces with dissipative elements in steel.

At the end of the isolated configurations (1) (2) and (3), the model was tested in fixed-base configuration (4), characterized and slightly damaged, then, the tamponages were demolished and the 12 dissipative braces were installed. These were used in configurations (5) and (6), required to simulate a rehabilitation intervention by dissipative braces. This intense test campaign allowed the comparison between the performances of the above 5 seismic protection systems.

Figure 4 shows the model with the undamaged masonry infills, in an isolated configuration and, after the demolition of the infills, with steel bracings. In all tests with base isolation, the disconnection from the table is possible because of the installation of an interface system made by sliding steel-PTFE devices, which are combined with several energy dissipation and/or re-centering systems (elastomeric isolators, steel isolators or SMA isolators). The interface structure between the shaking table and the model, Figure 5, was properly designed in order to activate the one or the other isolation system alternatively.

The bi-directional seismic excitation adopted is constituted by two records (NS and SW) of the 1997 Umbria-Marche earthquake (Italy), Colfiorito, opportunely scaled in time. The shaking table, with its 6 degrees of freedom, allowed the reproduction of component X and Y of the Colfiorito earthquake simultaneously, realizing a test situation similar to the real earthquake; only the tests with SMA isolator was performed with seismic excitation performed only in the Y direction. The model was equipped with 15 accelerometers (3 on the table and 3 for each floor of the model) and 3 laser displacement transducers to measure the movement of the isolation system; strain gauges were also used in order to measure the brace deformations.

Figure 4. Model with undamaged infills in isolated configurations and with steel bracings installed

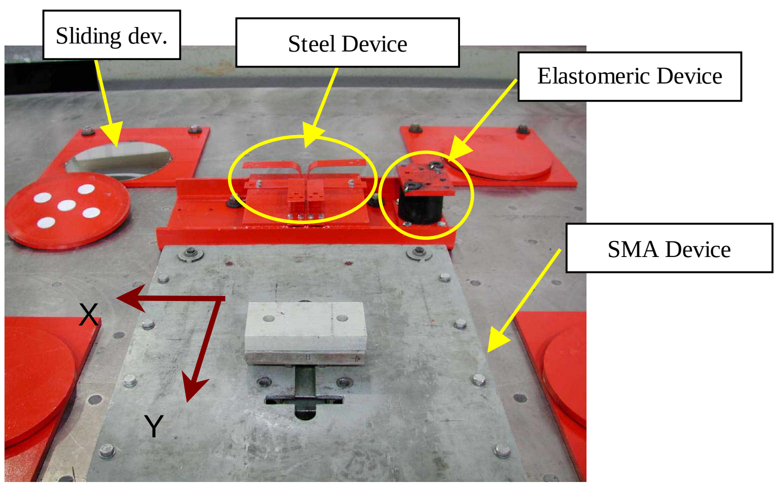


Figure 5. Detail of the interface structure and of the isolation systems

Figure 6 shows a brief selection of the results in terms of maximum accelerations. In particular it shows the comparison between the acceleration measured on the shaking table in the Y direction and that measured, in the same direction, on top of the structure. The reduction of the acceleration, in fact, allows to appreciate the isolation degree obtained with the base isolated configurations and the energy dissipation obtained with the bracings. It may be observed that with steel isolators the maximum top structure acceleration is 4.5 times reduced with respect to the base acceleration; instead, with elastomeric and SMA isolators this reduction is about 3 times, while with the braces it comes down to about 2. Moreover, during the conclusive tests with dissipative bracings installed, the maximum table acceleration reached more than 1.2g: after the test, the model was substantially damaged but had not collapsed. Instead, in the fixed-base configuration, pronounced damage of the masonry infills was detected for PGA of only 0.15g. Other elaborations of the results of these tests may be fond in Cardone [7].

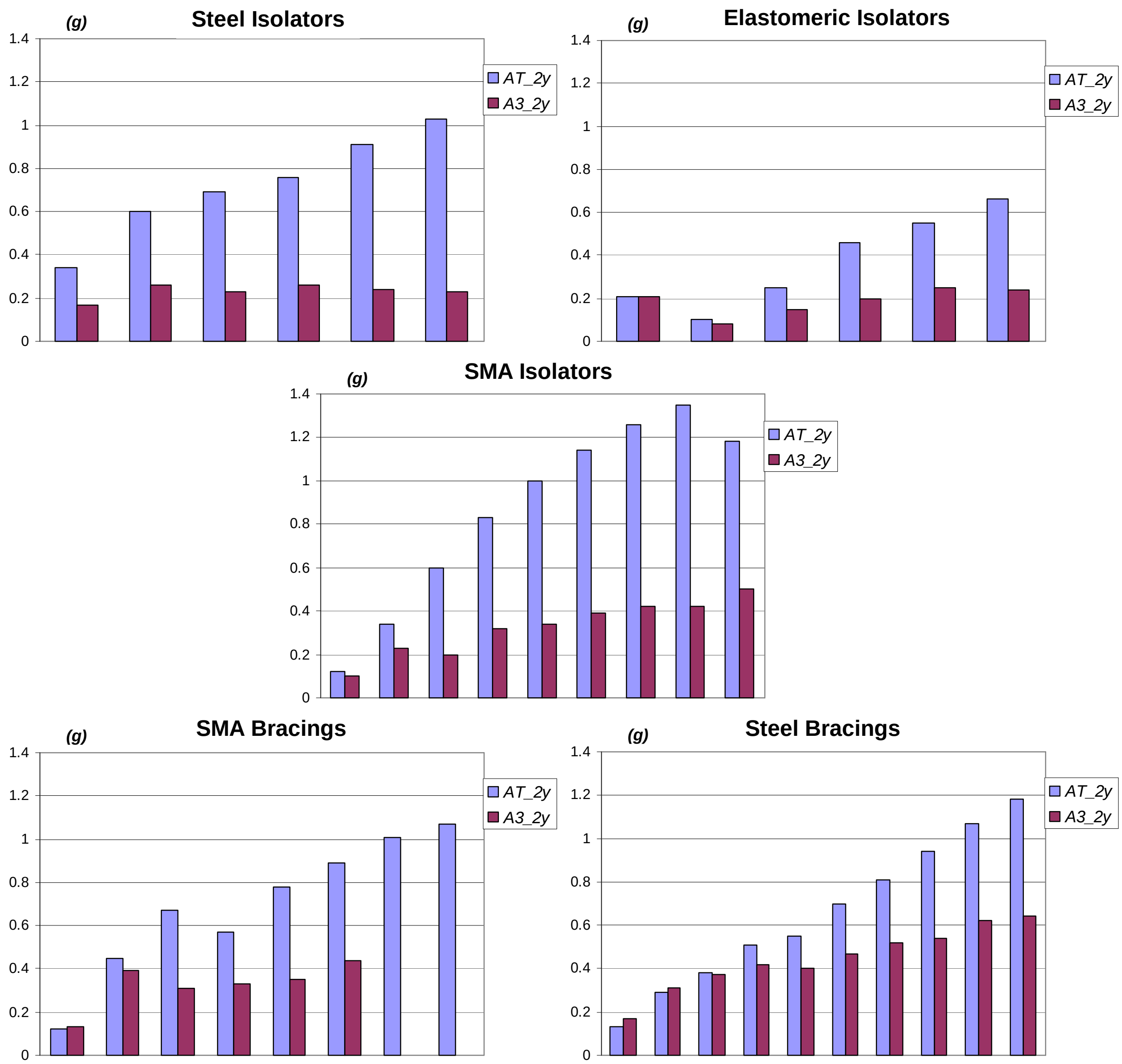
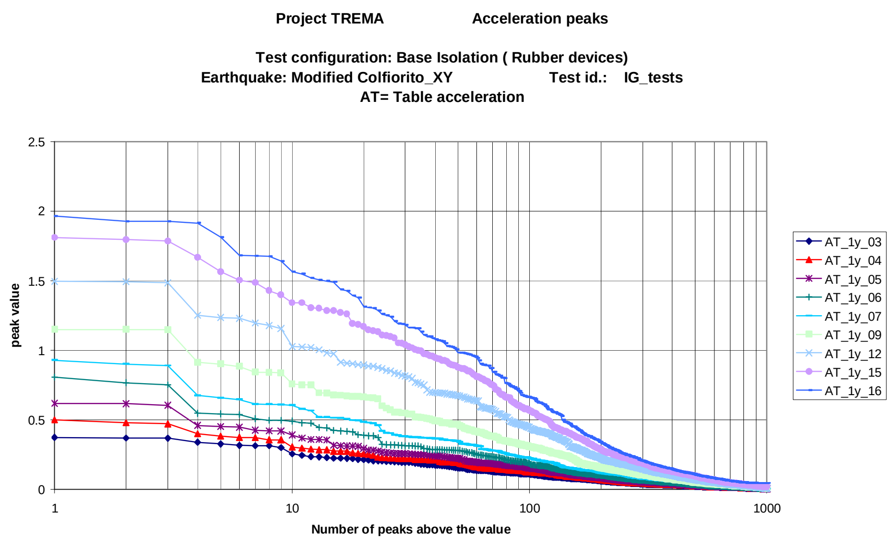
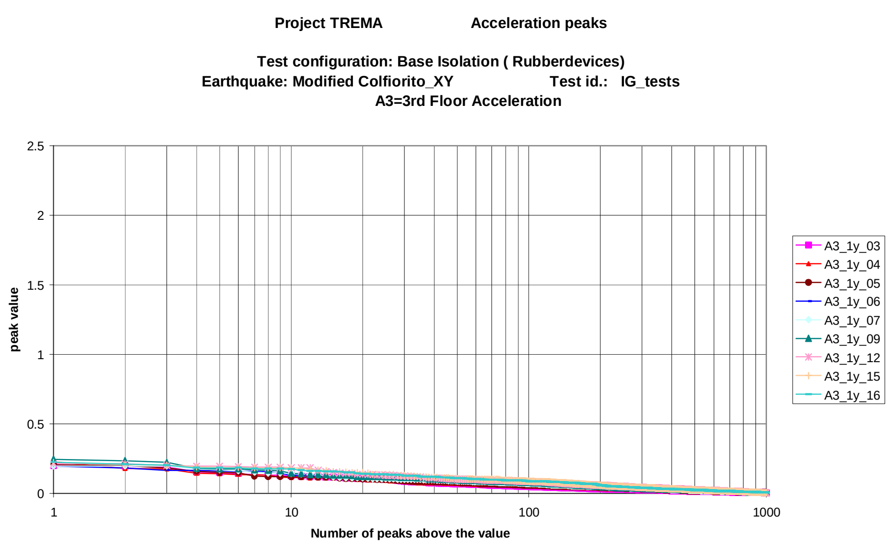


Figure 6. Comparison between the maximum shaking table (AT_2y) and top structure (A3_2y) accelerations in Y direction, for different configurations and PGA

The tests carried out on the third model, protected with elastomeric and SMA isolators, have fully confirmed the results of the previous tests. The structural model withstood, practically without suffering damage, to values of peak base acceleration of 1.6g. In this test, for a better visualization of the phenomenon, the accelerograms have been linked to repeat the input 3 times in the same test, consecutively. Figure 7 shows the values of relative acceleration maxima versus the number of repetitions in a time-history, for the shaking table (Figure 7a) and various isolation configurations (Figure 7b,c,d), for different PGA. With respect to the fixed base configuration (when an amplification of the input is observed, Figure 7d), in the isolated configurations it is possible to observe a large reduction of the maximum acceleration transmitted. It may be also observed that, especially when elastomeric isolators are installed, the response of the model is quite independent from the input intensity (Figure 7b).



(a)



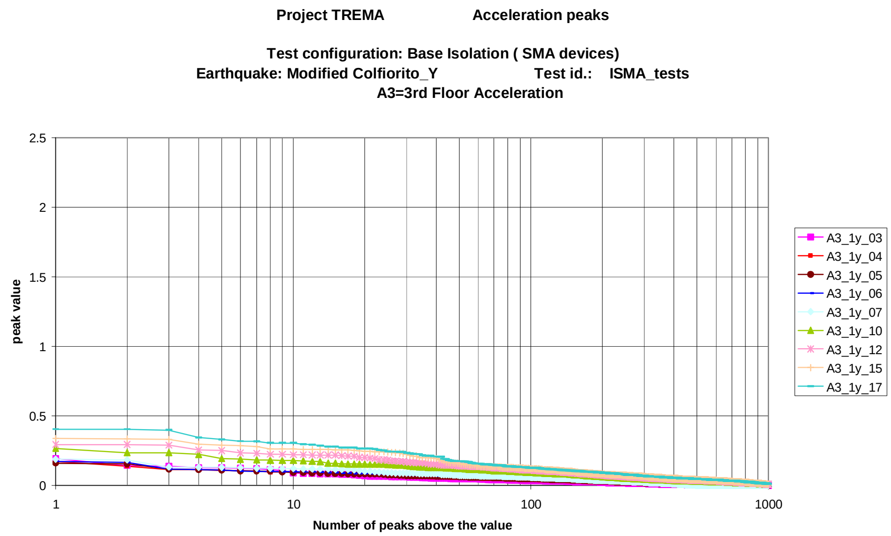
(b)

Figure 7 a,b. Acceleration peaks in Y direction. (a) shaking table, (b) top of the structure with elastomeric isolators.

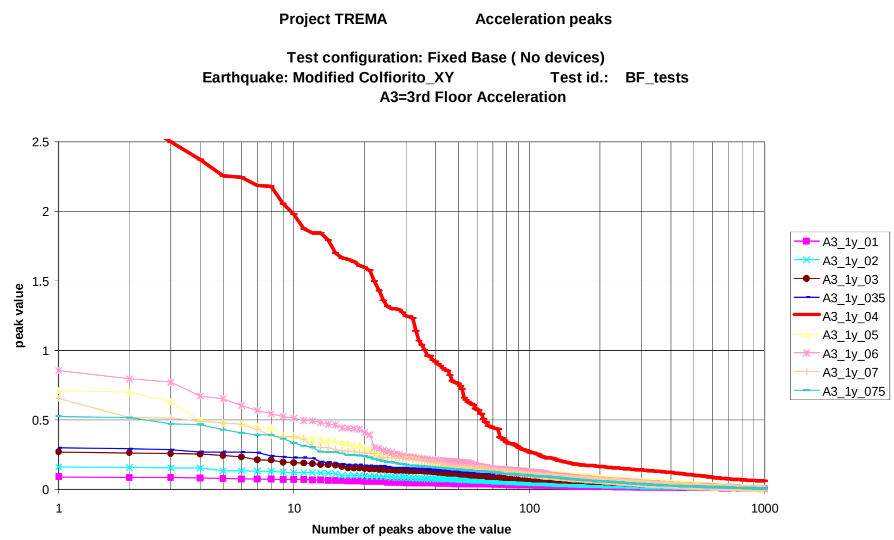
Finally in Figures 8 is showed the Integrated Exponential Acceleration Level (*IEAL*), proportional to the effective value of the floor absolute acceleration, evaluated as follows:

$$IEAL(a,t,Tc)=\left(\frac{1}{Tc}\cdot\int_{-\infty}^{t} a^2(t)\cdot e^{(\tau-t)/Tc}d\tau\right)^{1/2} \tag{1}$$

where T_C is the first characteristic period of vibration of the non-isolated structure. The IEAL represents a measure of the effective floor absolute acceleration transmitted to the structure in a time interval proportional to the characteristic period of the structure, i.e. it represents an index which evaluates the comfort and serviceability conditions for human and non-human contents of the structure and this appears particularly important for critical and strategic buildings, such as hospital, electrical plants, control rooms, etc.



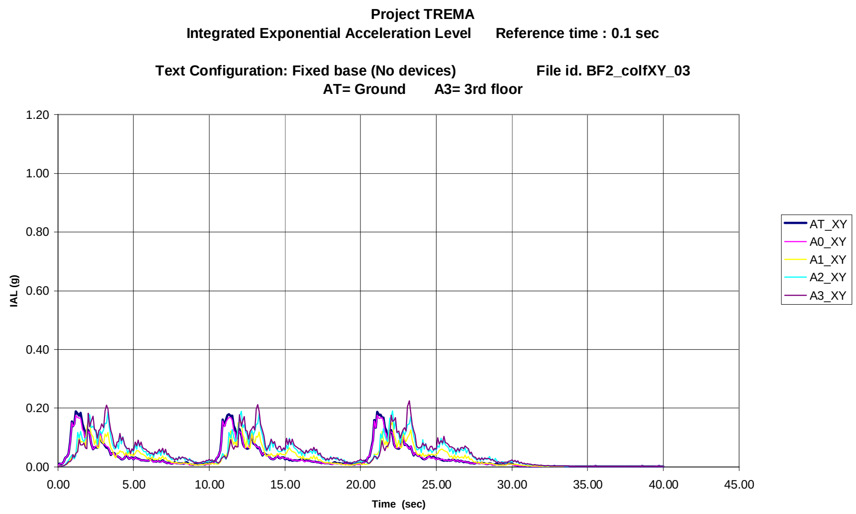
(c)



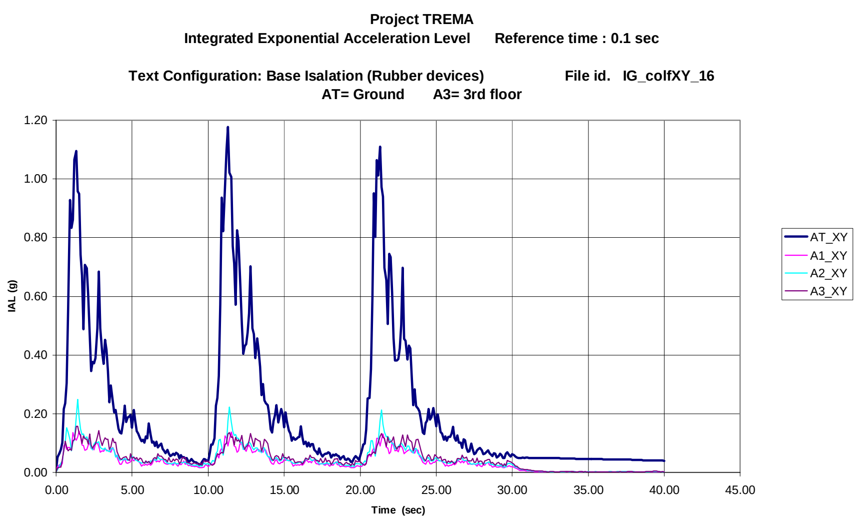
(d)

Figure 7 c,d. Acceleration peaks in Y direction. (c) top of the structure with SMA isolators, (d) top of the fixed-base model

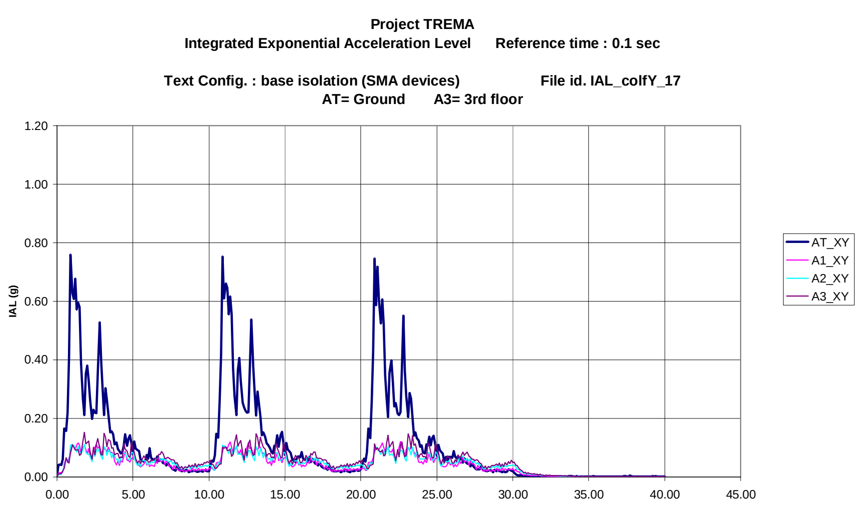
When the model was in the fixed base configuration (Figure 8a) there is an amplification of the IEAL of the acceleration transmitted to the structure, moreover this occurs in different times with respect to the maximum of the effective input. Instead, for the isolated configurations it may be observed a large de-amplification of the transmitted *IEAL*, and also that the maximum values occur simultaneaously with the maximum of the input. Besides, the response of the model, represented in Figures 8b and 8c, practically do not change for high input levels (1.6 ÷ 1.7g) from the input level at much lower levels (0.3g).



(a)



(b)



(c)

Figure 8. Integrated Exponential Acceleration Level IEAL, (a): fixed base 0.3g, (b) elastomeric isolators 1.6g, (c) SMA isolators 1.7g.

SEISMIC TESTS ON A STEEL STRUCTURE PROTECTED BY MEANS OF INNOVATIVE DISSIPATIVE BRACING SYSTEMS

Within a collaboration between ENEA MAT-QUAL section and Dept. of Structural and Geotechnical Engineering of University of Rome “La Sapienza”, in January 2003 has been developed a seismic test campaign on a two storey steel model frame (total mass of about 10 tons, already used in the past for other researches on different bracing systems, Ciampi [1]) protected by means of a new dissipative bracing system based on the elasto-plastic behavior of steel.

The proposed dissipative system is realized placing an Articulated Quadrilater (AQ), by means of diagonal tendons, at the center of the frame to be braced (see Figure 9); the AQ, is geometrically similar to the frame. The energy dissipation is realized by “C” shaped steel devices, placed on the diagonals of the AQ, and hinged to its vertexes (see again Figure 9). For significant story drifts, large displacements of the system are obtained, and the kinematic behavior of the AQ get all tendons in tension, and allows economical benefits in their sizing (the tendons, in fact, are never hardly compressed). In fact, while small drifts do not induce any axial force due to the kinematic behavior of the AQ, for large displacements the diagonal which becomes shorter varies its length more than the other one and so the entire bracing system is stretched. Thus the AQ, designed to remain quite elastic, has the main function to activate the compressed device during the motion.

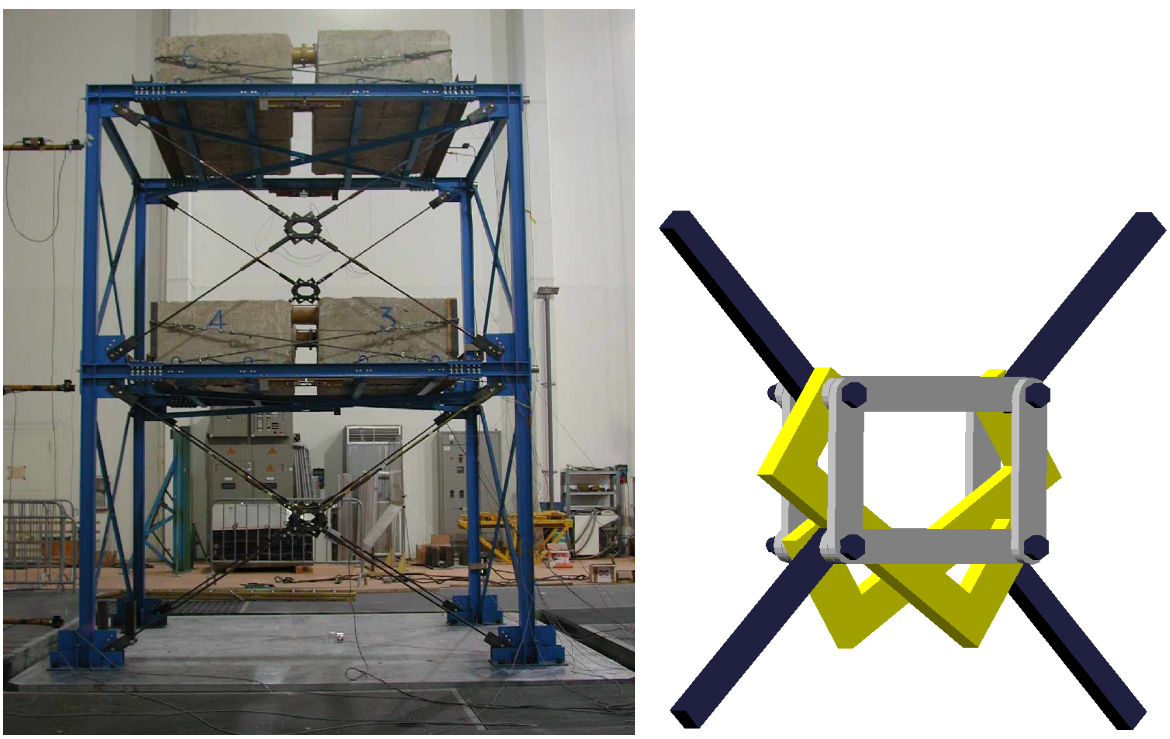


Figure 9. Test frame installed on the shaking table and 3D detail of the dissipative apparatus

The system has been designed for an existing steel frame: it is a three-dimensional steel frame, 3.00 m long, 2.40 m wide and 4.00 m high. It is composed of a couple of two-story, one bay, frames built using beams with HEA sections and floor structures, see Figure 9. To guarantee a small dissipative apparatus, it was decided to adopt a AQ which dimensions (170 × 260 mm), as regards to the frame, are scaled 1:17. As regard the design of the C-shaped devices, it was decided to optimize the protection for a PGA equal to 0.7 g.

The dynamical tests, performed in all these configurations, have consisted both in characterization and seismic test. For the seismic tests an artificial accelerogram compatible with elastic spectra of EC8 European Code, C.E.N. [6], called ‘Sofita’, and a natural record of Tolmezzo (Friuli, Italy, 1976 earthquake) have been used. The test frame has been equipped with the following transducers: n.6 seismic accelerometers, located at the table, and at both sides of the 1st and 2nd floor of the frame; n.3 laser displacement transducers, in order to measure the absolute displacement of the table and of the two floors; n.3 resistive displacement transducers, in order to measure the AQ deformations; n.8 strain gauges, in order to measure the deformation of the tendons, of the C-shaped devices and of the elements of the AQ.

The performances of the control system are shown in Figures 10, where the peak values of 1st story drift and total base shear, for Sofita input at different nominal PGA and for unbraced frame (ND configuration), for QA installed without dissipators (NC configuration) and with two dissipators in each quadrilater of first and second story (C2 configuration) are reported. The observation of the seismic behavior of the test structure, at different PGA, confirms the good performances of the proposed system, even at intensity levels different from the design one. In particular in C2 configuration, with respect to the unbraced frame (ND), 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%, corresponding to the design level of the device (PGA = 0.7g). More details on this experimentation may be found in Renzi [8].

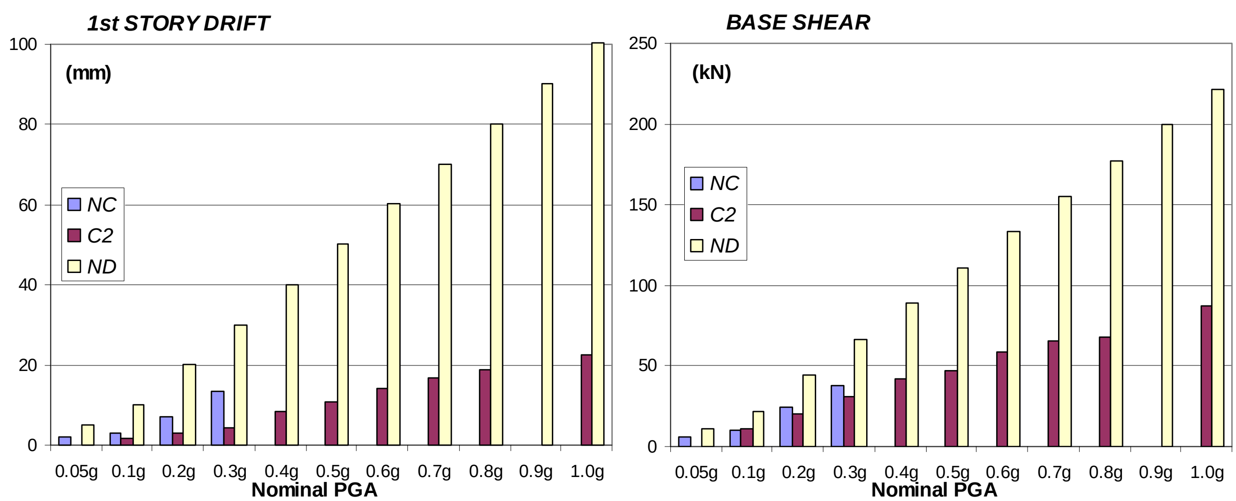


Figure 10. Maximum values of 1st storey drift and total base shear for different PGA, Sofita input

CONCLUSIONS

The large-scale shaking table experimentations illustrated in this paper, performed in 2002-2003 at the ENEA MAT-QUAL laboratories of R.C. Casaccia, clearly give the experimental evidence of the very good performances of different passive seismic protection systems applied in various structural configurations.

In particular, in the application to reinforced concrete and steel framed structures, it has been shown the performances of different base isolation systems, based on the use of steel-PTFE sliding devices, elastomeric devices, dissipative steel devices and re-centring Shape Memory Alloys devices, and of different bracing systems, based on dissipative steel devices, arranged in traditional and more innovative ways, re-centring Shape Memory Alloys devices and electro-inductive devices.

These experimental evidences confirm again the full applicability of these seismic protection systems in civil engineering structures, and should give a fundamental impulse to their wide application.

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