On the dynamic behavior of a new shear dissipater for the seismic protection of structures

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Abstract**—**The present paper describes a new dissipation device that can be utilized to reduce the seismic effects on civil engineering structures and preserve their structural integrity. The new device is made of aluminum and steel; it dissipates energy through the hysteretic behavior and the local plasticization of aluminum. It is a very simple device with a low cost of production. The proposed dissipater has been first tested using a monotonic type load in order to characterize it and to determine its mechanical parameters. Then its capacity to dissipate energy has been confirmed by a series of shaking-table tests on a 3D steel frame protected with these new devices. The frame has been subjected to a series of records from an impulsive earthquake such as Aigio allowing to determine the non-linear behavior of the dissipaters under severe working conditions, and to assess the efficiency of the device.

Keywords**—**Seismic protection, Steel-Aluminum devices, Hysteretic dissipaters, Characterization tests, Shaking-table tests.

I. INTRODUCTION

VIBRATION control is a subject that has received large attention in the field of earthquake engineering, and, accordingly, a variety of new techniques and devices have been developed for controlling structural vibrations induced by earthquake ground motions [1]. Among passive control devices, hysteretic dampers develop their damping from the energy dissipation due to the hysteretic behavior of their material (like steel) that are strained beyond the yield limit. They can provide relatively large dissipation for their size, and, thus, can be cost-effective.

Studies have been developed from numerical and experimental points of view on hysteretic dampers subject to near-field motions [2-4] to understand their efficacy during these kinds of seismic events. Comparisons have also been drawn between frames equipped with hysteretic dissipaters or friction dissipaters [5,6], and equipped with dissipaters or isolators [7]. The search of the optimum positioning of dissipaters in a frame has been developed in [8,9].

A critical drawback of such hysteretic dampers is that they cannot start to dissipate energy unless their materials receive inelastic excursions, since the materials' post-yielding hysteresis is the source of energy dissipation. Because of this drawback, they are effective only for larger earthquake excitations but fail in providing the required damping for smaller vibrations [10].

Moreover, most of the seismic codes are oriented to the concept of damage control: the structure should resist to minor or moderate ground motions with minimum structural damage, and may be damaged during large earthquakes without collapse and casualties. For these reasons, in recent years, structural steel has been used for the seismic control of structures. To overcome the problem that steel devices cannot be used for smaller vibrations since, in this case, they do not reach an inelastic deformation, dampers made of low yield steels [11], having yield stresses as small as 100 Mpa, have been designed [12-14]. The application of low-yield steel plates acting in shear allows a large amount of earthquake energy to be dissipated by complementary elements, which, therefore, serve as hysteretic dampers.

Actually, there are several types of dampers that could be profitably used for the seismic control of structures, but the combination of low-yield steel and shear panels is particularly effective. Firstly, the use of a low-yield material insures the damper to undergo large inelastic deformations at the first stages of the loading process, thus enhancing the energy dissipation capability of the whole system in a wide range of deformation demand. Secondly, the use of a plate subject to uniform in-plane shear forces allows the yielding of the material to be spread over the entire damper, ensuring a very large global energy dissipation capability. Thirdly, low-yield strength shear plates are characterized by a very stable hysteretic response up to large deformations, with a conspicuous strain-hardening under load-reversals and with limited strength and stiffness degradation arising from buckling.

The difficulty to find on the market low-yield steel has led to use the aluminum alloy, which could offer a similar behavior in terms of yield limit.

Shear devices have been designed either as large panels rigidly and continuously connected along the confining frame elements, or as elements installed in the frameworks of a building connected by bracing or column-type systems [15-23].

In this paper the behavior of new dissipation devices made with aluminum and steel panels is discussed. The panels

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reduce the seismic effect dissipating energy by shear deformation. To maximize the energy dissipation it is necessary that the panels start to deform plastically at relatively low forces; at the same time the device should still guarantee an adequate resistance before the final rupture.

Aluminum is characterized by a low-yield behavior, while the adequate resistance before failure is guaranteed by high-resistance steel stiffeners as better described in the following sections. The latter, in fact, can avoid the easy out-of-plane deformation of the aluminum plates. Therefore the aluminum panel presents some areas with facilitated plasticization, due to the lower yield point of the aluminum and the geometric configuration adopted.

Starting from the initial idea and on the basis of theoretical considerations and numerical simulations, the optimal geometry of the device has been defined. A detailed report on this first phase of design of the devices is summarized in previous works [24,25].

The optimized device has been tested for dynamic characterization, the shear force-deformation hysteresis has been obtained to evaluate the plasticization under loading. Quasi-static tests have been performed at the Technical University of Bari to check the mechanical characteristics of the device; then shaking-table tests have been performed at LNEC laboratory (Lisbon, Portugal) to check the real in situ behavior of these devices [25,26].

II. DESCRIPTION OF THE DISSIPATIVE DEVICE

The shear dissipating devices that have been designed, assembled and finally tested on a shaking-table are principally made of an inner 2mm-thick aluminum plate (AW-8006 EN573-3), which is symmetrically coupled to two 6.5mm-thick steel plates. The steel plates present some wide openings, their function in order to give a lateral stiffness to the device. In this way, the out-of-plane instability phenomena of the aluminum plate is avoided, or at least delayed. The geometrical configuration and the dimensions of the panels are shown in Figure 1.

Two different kinds of device have been considered depending on the two different connections between them. In the first solution, the three plates have been fixed with epoxy resin and uniformly bolted to the steel plates. In the second one, brazing has connected the plates. In the last junction modality, the initial geometry has been varied and two lateral 500x100x100 mm wings have been welded in place, to limit the lateral out-of-plane deformations of the plates. The sole use of epoxy resin to join the plates has been rejected, because this solution showed to be not effective during the preliminary tests. These tests, in fact, proved that the load transmission among the plates is critical for the device, since the plasticization of the aluminum central plate could be obtained if the same deformation of all the plates is achieved.

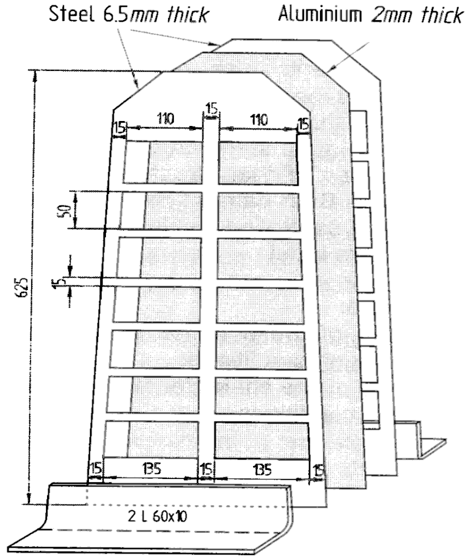

Fig. 1. Geometrical description of the panel.

III. TESTING

A. Preliminary quasi-static tests

Some preliminary tests have been performed at the Testing Laboratory “M. Salvati” of the Technical University of Bari to evaluate the mechanical characteristics of the shear panels, both in terms of global and local behaviors. The tested panels were made: a) with an aluminum plate and two steel reinforcements (referred as “aluminum shear panel”), b) with an inner steel plate and two steel reinforcements (referred as “steel shear panel”).

Figure 2a shows the experimental set-up for the preliminary tests. The Schenk cyclic force equipment was adapted to impress a shear force to the device simulating the force acting on the device and transmitted by an earthquake; the same force was then reproduced during a series of shaking-table tests (see sect. B).

To obtain a centered shear force at the base of the device, a steel “mirror” panel has been added, symmetrical to the one to be tested. The shear force on each panel was half the one measured at the loading cell.

The devices have been subjected to pulsating load cycles from zero to a maximum load value, the load peak has been increased at each cycle by 5 kN up to failure. All tests have been carried out in load control and all quantities have been measured and stored in real time during the test. The central panel showed a non-linear behavior starting from the beginning, at low values of the load.

The hysteresis curve of the aluminum shear panel is shown in Figure 2b. The aluminum panel started to plasticize at 2 mm displacement amplitude.

The dissipation capacity for small displacement has been greatly increased if compared with the results obtained on the steel shear panel; the last specimen required larger displacement (at least 5 mm) to yield. The reduced stiffness of the aluminum panel led to a more ductile behavior that constitutes the source of energy dissipation.

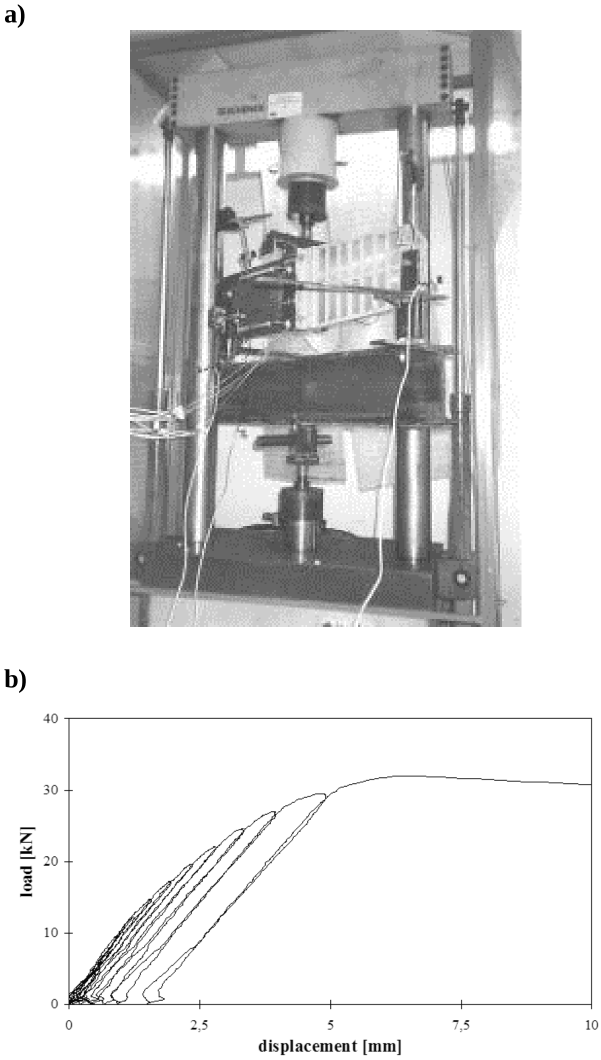

Fig. 2. a) Set-up for the quasi static tests; b) quasi-static test results for the aluminum shear panel.

The envelope curve of the hysteretic cycles represents the global mechanical characteristics of the panels. The linear part of the curves allows to identify the elastic stiffness and the elastic limit displacement that are reported in Table 1 for the aluminum panel; the results can be compared with the corresponding ones obtained for the steel shear panel.

Tab.1 - Elastic characteristics of the panels

	Elastic stiffness [kN/mm]	Elastic limit displacement [mm]
Steel Shear panel	4.56	3.23
Aluminum Shear panel	10.04	1.22

The optimization into the design of the device has been obtained analyzing the failure mechanism of the panels. The steel shear panel failed for a crack of the welding, which connected the panel to the clamping zone, so a better design should improve the welded joint.

The aluminum shear panel failure has been principally due to a global buckling, even if the panel behavior could be improved with a better welding execution. In fact a detachment of the aluminum plate from the steel welded fixed end has been observed.

On the basis of the quasi-static tests results [26] it was chosen to consider the aluminum shear device for the following shaking-tale tests because it showed a higher energy dissipation. However, the design of the device was improved:

1. A first type of panel has been designed by tightening the three plates by epoxy glue and a series of 108 M6(8.8) bolts.
2. A second type of panel has been designed by welding the three plates by brazing; in addition, two steel plates were welded laterally, once at each side of the dissipater, to cope with the out-of-plane forces.

B. Shaking-table tests

The shaking-table tests have been performed at the seismic division of the “Laboratorio National de Engenharia Civil” (LNEC) in Lisbon. The aluminum shear devices were installed on a frame mounted on a shaking-table (Figure 3a).

The shaking-table measures 5.6x4.6 m in plane and has three degrees of freedom, two horizontal and one vertical. The characteristics of the shaking-table are illustrated in detail in a report published by LNEC [25].

The measuring system was composed of LVDT displacement transducers, optical absolute displacement sensors located at the nodes of the frame and at the top and base of the dissipating devices, tridimensional piezoelectric accelerometers. Each side of the frame was identified by the four cardinal points; the earthquake direction is the East-West (Fig. 3b), and the panels (Figs. 4a,b) were installed on the North and South sides of the frame to behave for shear in the East-West direction of the signal.

The transducers measured:

- the accelerations in the three directions (vertical, transverse and longitudinal) of the shaking-table;
- the (vertical, transverse and longitudinal) accelerations at the top of the panel on the North and South sides of the frame;
- the (vertical, transverse and longitudinal) accelerations at the top and base of the frame’s columns on the N-W side;
- the displacements (in vertical and transverse directions) of the shaking-table;
- the displacements (in vertical and transverse directions) at the top and base of the frame’s columns on the South-East side;

- the displacements (in vertical and transverse directions) at the top and base of both panels.

Moreover, to catch the possible out-of-plane instability of the panel the longitudinal displacements in the middle of the external wings of the panels have been measured (Fig. 4b).

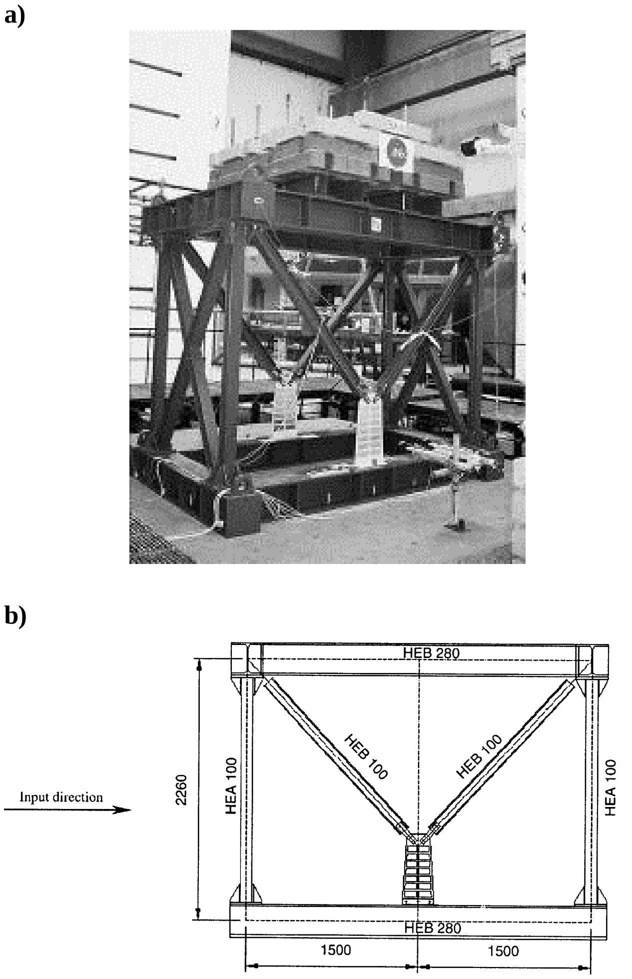

Fig. 3. a) Set-up for the shaking-table tests; b) geometric characteristics of the frame.

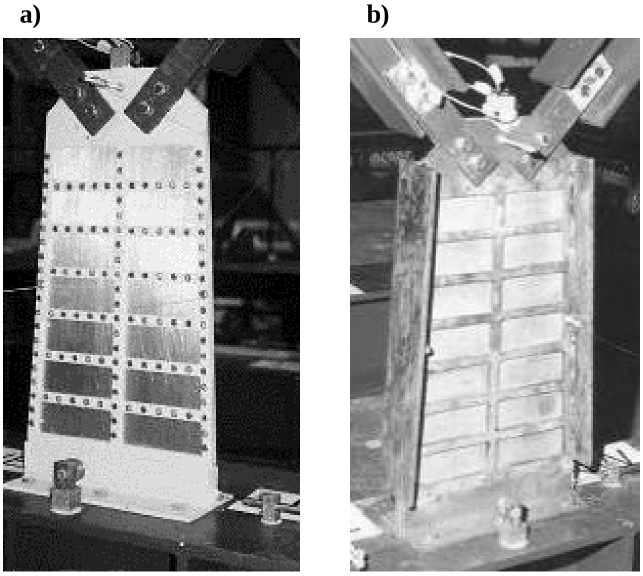

Fig. 4. a) The bolted panel and b) brazed panel on the frame for shaking-table tests.

Characteristics of the test frame

The frame utilized for the tests is made of four HEA100 columns and HEB280 beams, the V bracing system consists of HEB100 diagonals connected to the upper nodes of the frame and the top of the panel through M10 bolts. The frame is stiffened with two diagonals to avoid torsional vibrations of the frame during the tests (see Fig. 3a).

A mass of 85 kN was added on the top of the frame to simulate the masses that usually act on a real structure.

The structure without panels and bracing (bare frame) has been also tested at a low level of seismicity; the results have been compared with those obtained from the frame protected with the dissipating panels.

Characteristics of the earthquake

Aigio earthquake (EW component) (Figs. 5a,b) scaled by a factor of two has been utilized as earthquake simulating signal for the tests. It is characterized by a maximum peak ground acceleration of PGA=0.54g and a duration of 6 s.

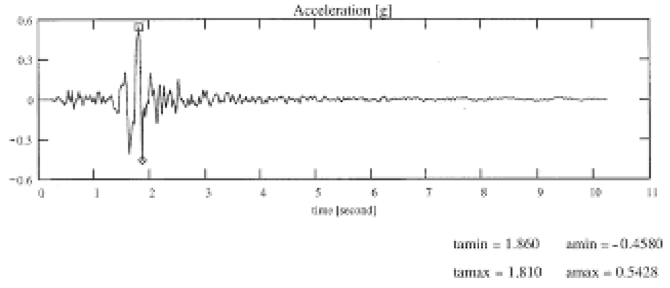

Fig. 5. Aigio earthquake register utilized for the shaking-table tests. Transversal acceleration.

The choice to utilize an impulsive earthquake like Aigio is motivated by the necessity of catching the dissipative capacity of the panels. It means to require that the device enters soon the plastic field. The tests were performed at increasing levels of peak ground acceleration. A "pink noise" was applied to the structure after a sequence of tests using Aigio input, to evaluate the natural frequencies of the frame, and to identify possible changes of its dynamic characteristics.

Table 2 shows the dynamic test program on the protected and unprotected frames. Tests on the frame protected once with bolted devices and once with brazed panels have been performed. In addition and for comparison aims, tests on the structure without any dissipating device have been performed too.

Tab. 2 - Dynamic tests program and results

Test on bolted panels	Signal	Nominal Acceleration/g	Measured Acceleration /g	Natural Frequency [Hz]
B1	Pink noise			7.45
B2	Aigio	0.100	0.09	
B3	Aigio (2r)*	0.200	0.186	
B4	Aigio	0.300	0.311	
B5	Pink noise			7.42
B6	Aigio (2r)	0.600	0.500	
B7	Aigio (2r)	0.600	0.499	
B8	Aigio (2r)	0.600	0.614	
B9	Aigio (2r)	0.700	0.931	
B10	Pink noise			6.77
B11	Aigio (2r)	1.000	1.181	
B12	Pink noise			5.67
B13	Aigio (6r)	1.000	0.912	
B14	Aigio (6r)	1.200	1.224	
B15	Pink noise			5.88
Test on brazed panels	Signal	Nominal Acceleration/g	Measured Acceleration /g	Natural Frequency [Hz]
W1	Pink noise			6.97
W2	Aigio (6r)	0.200	0.213	
W3	Aigio (6r)	0.400	0.375	
W4	Pink noise			6.52
W5	Aigio (6r)	0.600	0.501	
W6	Pink noise			5.52
W7	Aigio (6r)	0.800	0.539	
W8	Aigio (6r)	0.800	0.780	
W9	Pink noise			4.58
W10	Aigio (6r)	1.000	1.144	
W11	Aigio (6r)	1.000	1.054	
W12	Aigio (6r)	1.200	1.300	
W13	Pink noise			4.81
Test on bare frame	Signal	Nominal Acceleration/g	Measured Acceleration /g	Natural Frequency [Hz]
F1	Pink noise			2.76
F2	Aigio (6r)	0.150	0.130	
F3	Aigio (6r)	0.250	0.252	
F4	Pink noise			2.76

* "r" stands for "repetitions" of Aigio signal.

IV. TESTS RESULTS

The tests performed with increasing PGA showed that a large dissipation capacity has been offered by both types of aluminum shear panels (bolted and brazed).

During the first tests at a low seismic intensity no damage on the devices appeared, but the cycle was already quite large, showing a dissipative capacity at this level. Figs. 6a,b show the hysteresis cycles of both panels (bolted and brazed) at a low seismic intensity level.

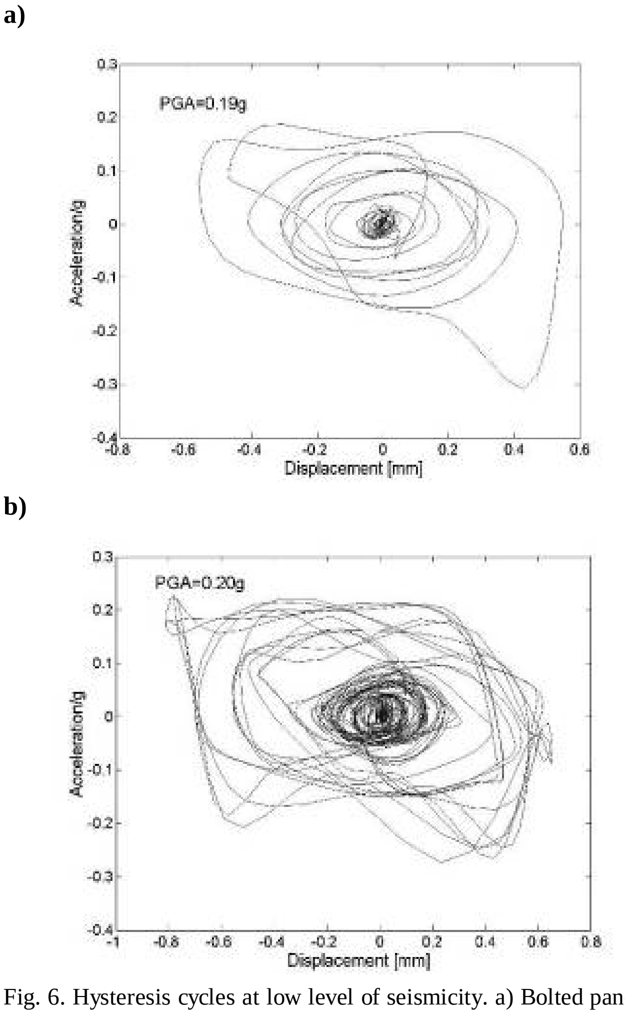

Fig. 6. Hysteresis cycles at low level of seismicity. a) Bolted panel; b) Brazed panel.

When the PGA increases, the hysteresis cycles become wider and the energy dissipated is higher (Figs. 7a,b). In addition, it can be noticed that the panel does not lose its initial stiffness. Moreover, the permanent deformation and the consequent loss of planarity of the panels, verified at medium-high earthquake intensities, does not seem to affect their dissipative capacity.

At a higher seismic level, the bolted panels showed some buckling phenomena. In particular, the out-of-plane inflection started at PGA=0.5g (Fig. 7a). The brazed panels have been subjected to the same deformation only at high levels of PGA because of the presence of the lateral stiffeners on the wings.

Two transducers were positioned in order to measure the displacements orthogonal to the input direction of the device corresponding to the out-of-plane deformation. Figure 8a shows the results for the bolted panels at low level of seismicity.

a)

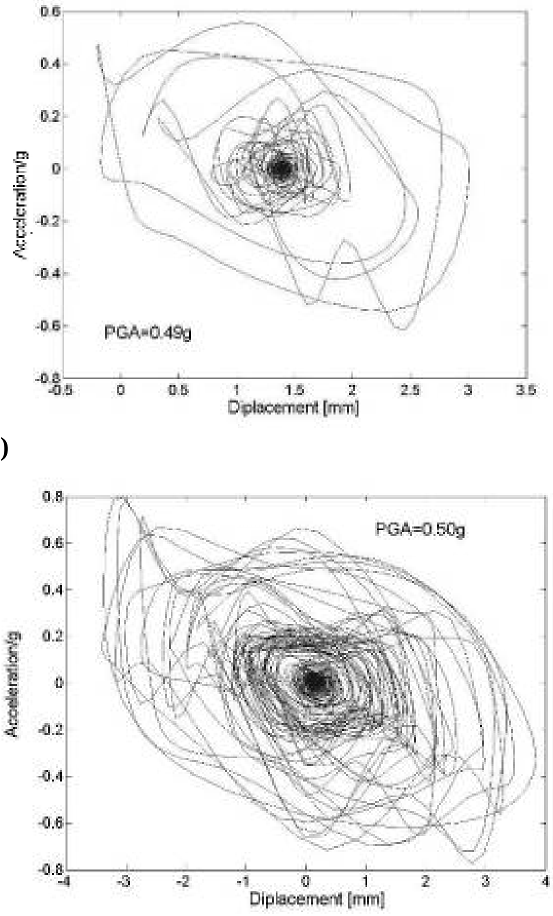

Fig. 7. Hysteresis cycles at high level of seismicity. a) Bolted panel; b) brazed panel.

Figs. 8b, 9a,b show the out-of-plane displacement of the panels due to six repetitions of the Aigio earthquake record, each repetition producing an increment into the permanent deformation in both panels.

a)

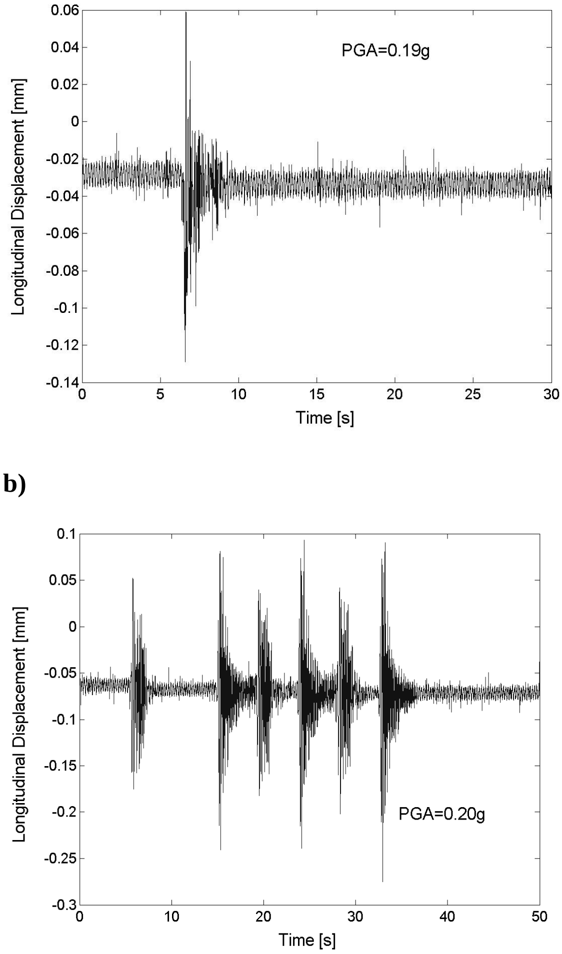

Fig. 8. Out-of-plane displacement at low level of seismicity. a) bolted panel; b) brazed panel.

a)

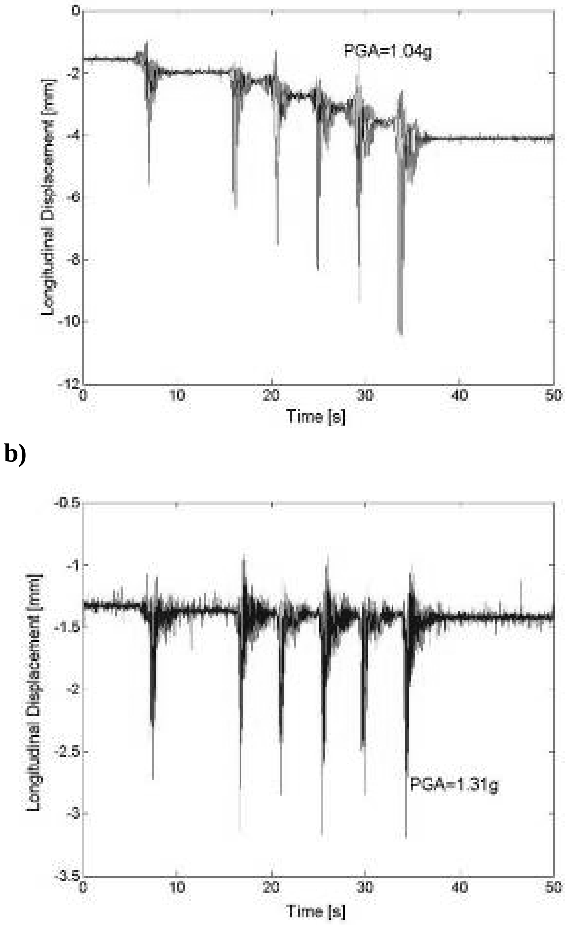

Fig. 9. Out-of-plane displacement at high level of seismicity. a) Bolted panel; b) brazed panel.

Moreover, the wings added to the brazed panel reduced the out-of-plane deformation and assured a better cohesion between the plates. However, it reduced the plasticization and, consequently, the dissipative capacity of the brazed panels that is effective at high levels of seismic intensity.

Figure 10 shows the final deformed configuration of the bolted panel at the end of the test with a clear out-of-plane deformation.

Figure 11 shows the maximum displacement at the top of the frame's column versus to the input PGA. At low level of seismic intensity, the protected frame in both cases of bolted and brazed devices, as expected, had smaller displacements compared to the bare frame. For medium levels of the input intensity the bolted panels gave a better response with a reduced displacement at the top of the column. At high levels of the input intensity the brazed panels gave smaller displacements, probably due to the presence of the wings that initially (at low PGA) reduced the inelastic deformation but did not limit the plasticization for large earthquakes.

This result proves how critical the design of this type of shear dissipaters can be, since an added stiffness could reduce the efficiency in dissipation. In the meanwhile the problem of buckling should be taken into account to avoid instability problems.

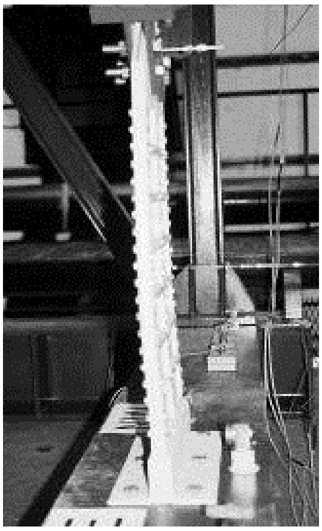

Fig. 10. The bolted panel after the test.

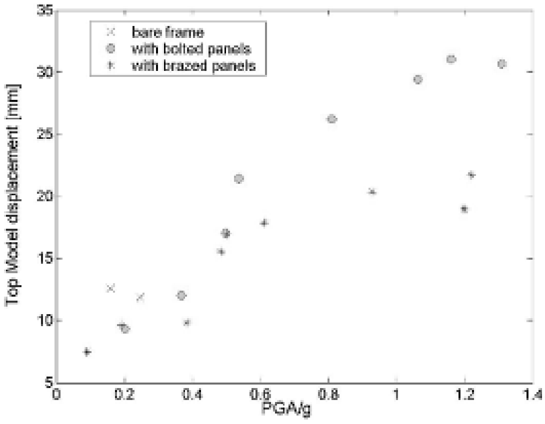

Fig. 11. Maximum transverse displacements of the top of the frame at increasing PGA.

Figs. 12A and B show, respectively, the displacement and acceleration time-histories of:

- the frame with bolted panels at PGA=0.20g,
- the frame with two brazed panels at PGA=0.20g,
- the bare frame at PGA=0.15g.

The added damping and the reduced values of displacement and acceleration due to the presence of panels assess the efficiency of the proposed devices for small earthquake ground motions.

V. CONCLUSIONS

The new aluminum-steel dissipater here proposed has shown to be able to dissipate a large amount of seismic energy, limiting and concentrating the seismic damage on itself. The simple device has the advantage of an easy replacement that allows to rapidly restore the functionality of a building.

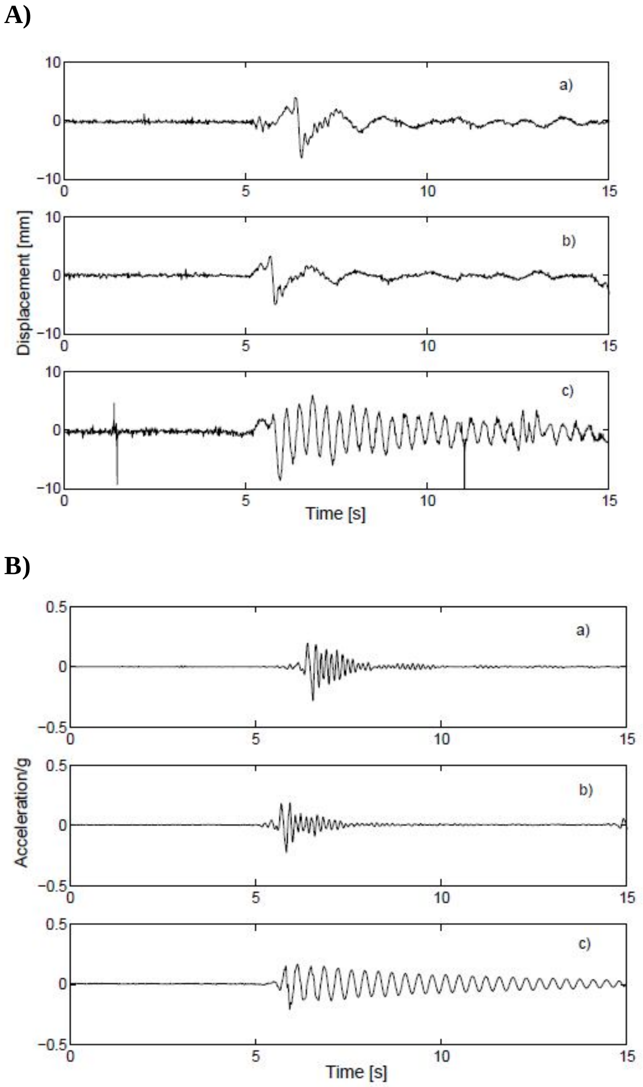

Fig. 12. A) Displacement time-history and B) acceleration time-history at the top of the column of: a) frame with bolted panels PGA=020g; b) frame with brazed panels PGA=0.20g; c) bare frame PGA=0.15g.

A series of tests performed on a frame protected with the proposed shear panels have shown their capability to dissipate a large amount of seismic energy. The tested frame, in fact, was found to withstand even catastrophic events without damage. The localized damage was exclusively concentrated in the panels.

Two types of dampers have been tested on the shaking-table, bolted and brazed panels. The comparison of the experimental results showed that the total behavior of the brazed panels was not completely satisfactory for the lower plasticization capacity and the delamination danger that showed up in the most severe test conditions. The first problem was due to the presence of the wings in the brazed panels that had been added with the aim of guaranteeing better cohesion of the plates. However, they negatively influenced the plasticization capacity since this inelastic phenomenon appeared at high levels of the seismic intensity.

Both bolted and brazed panels suffered of the out-of-plane deformations, the buckling phenomenon of the aluminum plate and permanent deformations.

From the results the bolted specimen showed the most efficient response, while in the brazed connection the existence of imperfectly adherent areas led to delamination. However, this result was not due to a bad junction execution, but to manufacturing difficulties.

The test results proved the importance of an optimum design of the device to avoid buckling phenomena, to transfer properly the shear force among the plates, and to make possible the plasticization at low levels of the input seismic intensity. To solve these problems in the damper design the choice of the stiffeners, the type of connections among the plates and the plate thickness are crucial points to be accurately considered.

ACKNOWLEDGMENT

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