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SHEAR PANEL FOR SEISMIC PROTECTION OF STRUCTURES

Dora FOTI[1] and Alessandra ZAMBRANO[2]

SUMMARY

The paper presents a dissipation device that can be used to preserve the structural integrity of civil engineering structures subjected to seismic loads. The proposed device is a shear panel made of aluminium and steel, which dissipates energy through the hysteretic behaviour and the local plasticization. It is a very simple device having the advantage of a low cost of production.

The proposed shear panel has been tested using a monotonic type of experiment that has led to optimise its design and to define its main characteristics, then its dynamic behaviour has been obtained through some tests on a 3D shaking table. A frame with these devices has been subjected to a series of accelerograms to determine its response under ground motions of different intensities and to assess their efficiency.

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. Among passive control devices, tuned mass dampers (TMDs), tuned liquid dampers (TLDs), viscous dampers, and hysteretic dampers are particularly popular. TMDs, TLDs and viscous dampers are very efficient in controlling vibrations produced by small ground motions, but they do not dissipate sufficiently during large ground motions. Moreover some problems related to their weight (as for TMDs, TLDs) or to their accommodation (as for viscous dampers) into the structure limit their use.

Hysteretic dampers develop their damping characteristics from the energy dissipation due to the hysteretic behaviour of their material (like steel alloy) that are strained beyond the yield limit. They can provide relatively large dissipation with small dimensions of the devices, and thus can be cost-effective.

A critical drawback of such hysteretic damper is that they cannot function as dampers 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 large earthquake excitations but fail in providing the required damping for small vibrations.

[1] Department of Civil and Environmental Engineering, Politecnico di Bari, Italy, dfoti@poliba.it
[2] Department of Civil Engineering, Seconda Università di Napoli, Italy, alessandra.zambrano@unina2.it

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 a minimum structural damage, and may be damaged during large earthquakes without collapse and loss of lives. For these reasons structural steel has been used for seismic control of structure in recent years, but to overcome the problem that steel devices can not be used for smaller vibrations, since in this case they have not inelastic deformations, dampers made of low yield steels (Saeki [1]), having a yield stresses as small as 100Mpa, have been designed (Nakashima [2, 3], Elgaaly[4]).

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. First, the use of 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 subjected to uniform in-plane shear force 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 panels 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.

Shear devices have been designed either as elements installed as large panels rigidly and continuously connected along the confining frame elements, serving also as basic enclosure system plates, either as elements installed in the frameworks of a building connected by bracing or pillar type system. Recently a large attention to this type of dissipation systems has been employed by several researchers (Saeki [1], Nakashima [2, 3], Elgaaly [4], Bozzo [5], De Matteis [6], Yamada [7],Yamada [8], Fulop [9]).

The difficulty to find on the market low-yield steel has pushed to use aluminium, which could offer a similar behaviour to low-yield steel.

In this paper the behaviour of a new dissipation device, a shear panel made of aluminium and steel, is discussed. To maximize the energy dissipation, it is necessary that the panel starts to deform plastically at relatively low forces, and they could still guarantee an adequate resistance before the final rupture. The aluminium is characterized by a low-yield behaviour. To avoid the easy out-of-plane deformation of the aluminium plate, high-resistance steel stiffeners have been added. Therefore the aluminium panel presents some area with facilitated plasticization, due to the lower yield point of the aluminium material and to the adopted geometric configuration.

On the basis of theoretical considerations and numerical simulation, the optimal geometry of the panel has been defined. A detailed report about this first phase of the design of the device is summarized in a previous work (Foti [10]).

The optimised device has been tested with some quasi-static test performed in the laboratory “M.Salvati” of the Politecnico di Bari (Italy) to verify the design. The shear force-deformation hysteresis has been obtained to evaluate the plasticization under loading.

Subsequently, some shaking table tests have been performed at LNEC laboratory (report LNEC 304/00 [11], Foti [12]) to simulate the real *in situ* behaviour of these types of devices installed in a steel frame. Two types of panels have been rested, they have the same dimensions but differ for the type of connection among their components.

DESCRIPTION OF THE DISSIPATIVE DEVICE

The two types of shear panels, that have been tested on the shaking table, are principally made of a 2mm-thick aluminium plate (AW-8006 EN573-3) which is symmetrically coupled to two 6.5mm-thick steel plates. The steel plates presents some wide openings, its function is to offer a lateral stiffness to the device. In this way, the out-of-plane instability phenomena of the aluminium plates is avoided, or at least delayed. The geometric configuration and the dimensions of the panels are shown in Figure 1.

The two different kinds of panel differ only in the means of connection of the plates. In the first solution, the three plates have been fixed with epoxy resin and uniformly bolted on 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 500x100x100mm wings have been welded in place, to limit the lateral out-of-plane deformations of the panels. The sole use of epoxy resin to join the plates has been rejected, because this solution has not been effective during the preliminary tests.

In fact, these tests proved that the load transmission among the plates is critical for the device, since the plasticization of the aluminium plates could be obtained if the same deformation of all the plates is achieved.

The bolted specimen had the most efficient response, while in the brazed connection the existence of imperfectly adherent areas led to delamination. This result is not due to bad junction execution, but to manufacturing difficulty.

In the following section the preliminary tests results, that have been conducted to the optimal design of these two shear panels are discussed, in order to motivate the adopted choice.

THE TESTS

Preliminary quasi-static tests

Some preliminary tests have been performed at the Laboratory of the Politecnico di Bari, to evaluate the mechanical characteristics of the shear panels, both in terms of global and local behaviour. The previous tested panels were made: a) one with an aluminium plate and two steel reinforcements (referred as “aluminium shear panel”), b) another with an inner steel plate and two steel reinforcements (referred as “steel shear panel”).

The aluminium shear panel has been obtained joining the aluminium plate and the steel stiffeners in two different manners: a simple bondage by means of epoxy glue or, alternatively, a connection made with bolts equally distributed on the panel, whose geometric description is shown in Figure 1.

An analogous panel made in all steel has been tested to compare the result with the panel made in aluminium. This steel panel is composed by an inner steel plate (2mm thick) inside the typical alveolar shape stiffeners (15mm thick); the dimensions are the same of the aluminium shear panel. The inner plate and the stiffeners have been welded together.

The testing machine is a Schenck servo-idraulic with a static capacity of 250kN (Figure 2).

A pulsating shear load has been applied at one end of the panel and the corresponding displacement has been measured. Moreover the local strain has been measured in order to verify the local yielding and the energy dissipation capacity into the device.

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 hysteresis cycles of the aluminium shear panel is shown in Figure 3. The aluminium panel started to plasticize at 2mm displacement amplitude. The dissipation capacity for small displacement is highly increased if it is compared to the results obtained on a specimen made entirely of steel of the same dimensions, this specimen required larger displacement (at least 5mm) to yield. The reduced stiffness of the aluminium panel led to a ductile behaviour that constitutes the source of energy dissipation. The envelope curve of the hysteretic cycles represents the global mechanical characteristics of the panels. The linear part of the curves allow to identify the elastic stiffness and elastic limit displacement that are reported in Table 1 for both type of panels, in order to compare their different behaviors.

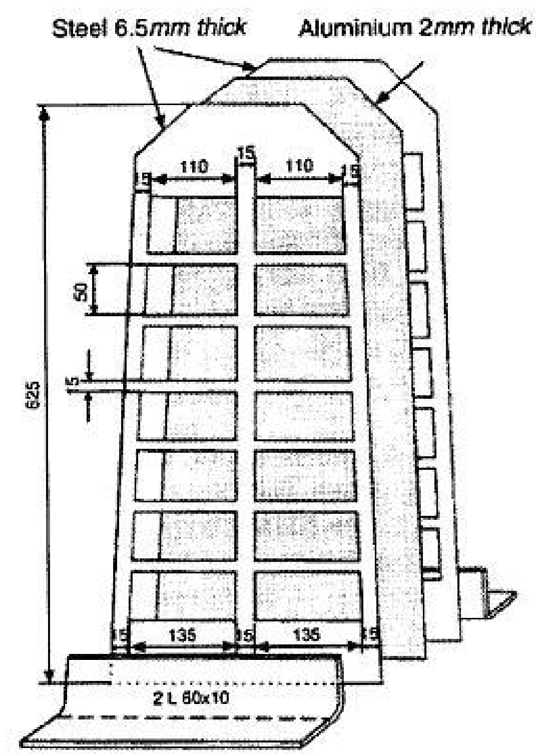

Figure 1 – Geometric description of the aluminium shear panel.

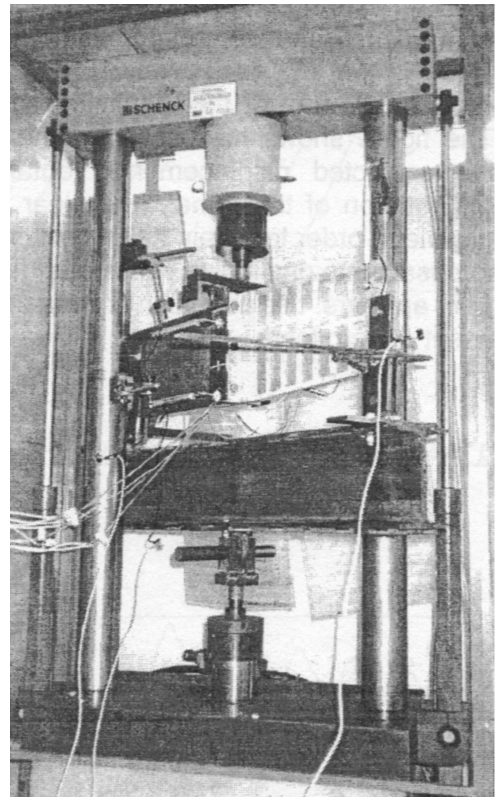

Figure 2 – Quasi-static tests.

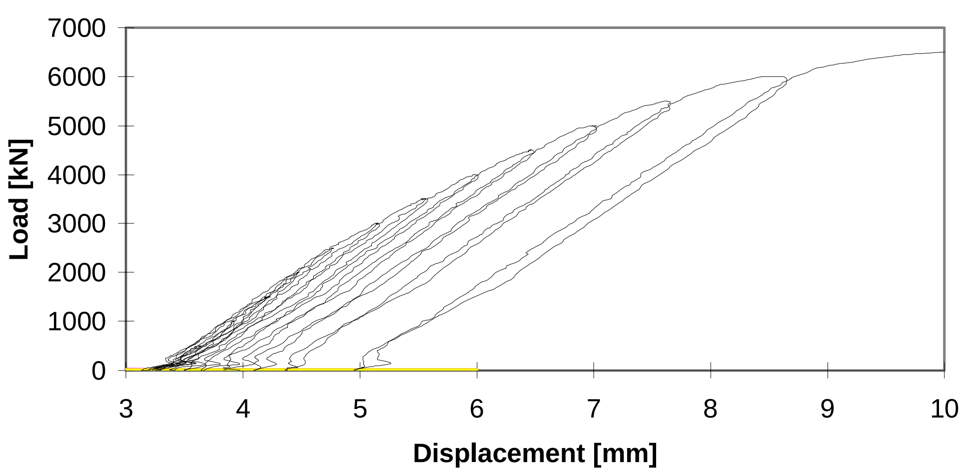

Figure 3 – Aluminium shear panel: quasi-static test results.

Table 1 - Elastic characteristic of the panels

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

The analysis of the failure mechanism of the panels yields to the following considerations:

a) the steel shear panel failed for a crack on the welding which connected the panel to the clamping zone, therefore a better design should improve the welded joint.
b) The panel failure of the aluminium panel was principally due to a global buckling, and a detachment of the aluminium plate from the steel welded fixed end has been observed.

On the basis of the quasi-static results the design of the panel was improved:

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

Subsequently, these two types of devices with aluminium plates and steel reinforcements, characterized by different junctions, have been tested on a shaking table, as next section will show the test protocol and the results.

Shaking table tests

The shaking table tests were performed at the "Laboratorio National de Engenharia Civil" (LNEC) in Lisbon. The two types of devices, described in the previous paragraph, were mounted on a frame connected to a shaking table (Figure 4).

The shaking table measures 5.6x4.6m 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 (LNEC report 304/00 [12]).

The measuring system is composed of LVDT displacement transducers, optical absolute displacement sensors, three-dimensional piezoelectric accelerometers. Measurements have been taken at the node of the structure, at the top and base of the panels and at the shaking table. The earthquake direction is indicated in Figure 5, and the panels (Figure 6 and 7) are installed on two sides of the frame to work in plan for the earthquake direction (referred as transverse direction).

The transducers have measured:

1. the accelerations in the three directions (vertical, transverse and longitudinal) of the shaking table,
2. the (vertical, transverse and longitudinal) accelerations at the top of the two panels,
3. the (vertical, transverse and longitudinal) accelerations at the top and base of the frame columns,
4. the displacements (in vertical and transverse directions) of the shaking table,
5. the displacements (in vertical and transverse directions) at the top and base of the frame columns,
6. the displacements (in vertical and transverse directions) at the top of both panels.
7. the displacements (in transverse direction) at the base of both panels.

Moreover to catch the possible out-of-plane instability of the panels the longitudinal displacements in the middle of the external wings of the panels have been measured (Figure 7).

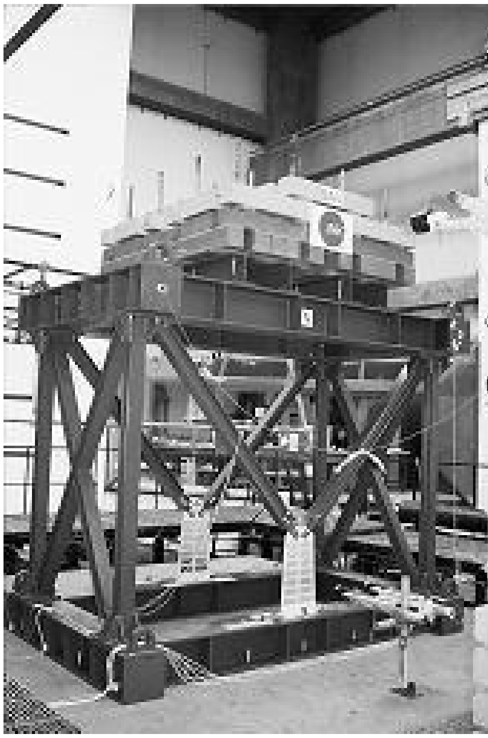

Figure 4 – Frame on shaking table.

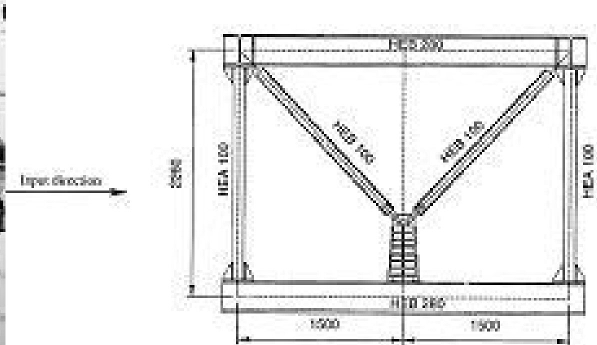

Figure 5 – Geometric characteristics of the frame.

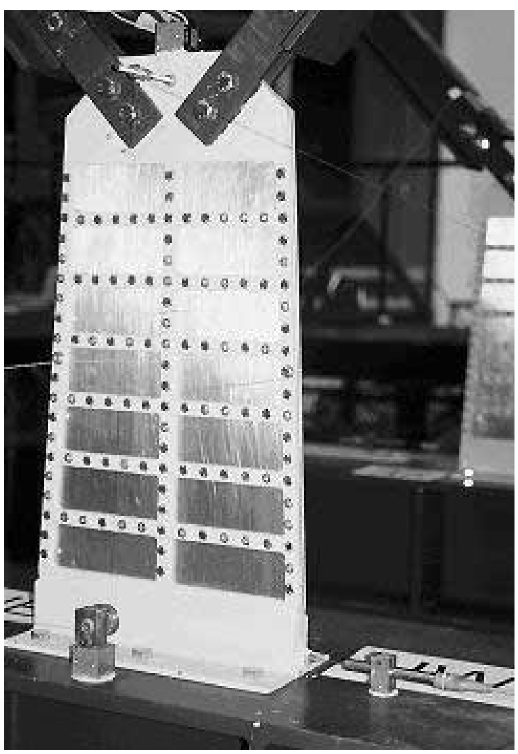

Figure 6 – The bolted panel.

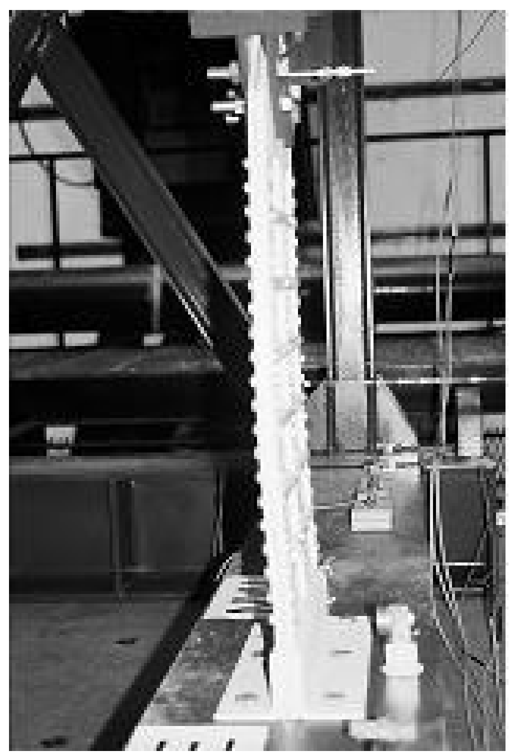

Figure 7 – The bolted panel after the test.

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 oscillations of the frame (see figure 4).

A mass of 8500 kg is added to 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 to obtain some comparisons with the results of the frame with panels for a low level of seismic event. The pink noise signal have allowed to identify the first modal frequency of 2.76 Hz.

Characteristics of the earthquake

The earthquake used in the test is the Aigio (E-W component) earthquake (Figure 8) scaled by a factor of two. Figure 9 shows its spectrum. This input is characterized by a maximum peak ground acceleration of PGA=0.54g and a duration of 6s. This choice of an impulsive earthquake as Aigio is motivated on the necessity of catching the dissipative capacity of the panels. The tests were performed at increasing level of the peak ground acceleration. A “pink noise” has been applied to the structure after a sequence of tests using the Aigio input, to evaluate the natural frequency of the frame, and to identify possible changes of its dynamic characteristics. Table 2 shows the signal applied in each test, the number of sequences of earthquake record in each signal, the nominal and measured accelerations on the table and the natural frequency of the frame obtained with the pink noise test. Tests B1-B15 have been performed on the frame with the bolted panels. PGA has been increased from a value of 0.1g to 1.2g. Tests W1-W13 have been performed on the frame with the brazed panels. The input in each test is a sequence of six Aigio earthquakes with increasing PGA from 0.2g to 1.2g.

Finally the structure has been tested without any dissipation devices (tests F1-F4 in table 2).

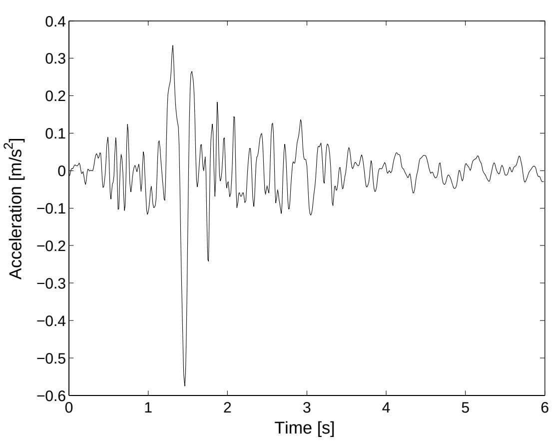

Figure 8 – Aigio earthquake, E-W component (1995).

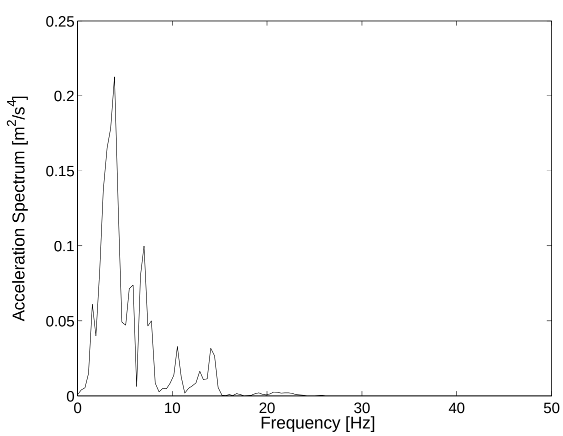

Figure 9 – Acceleration spectrum of the Aigio earthquake.

Table 2 -Test conditions: signals and recorded natural frequency.

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

TEST RESULTS

The tests performed with increasing PGA have demonstrated that a large dissipation capacity have been offered by both types of aluminium shear panels (brazed and bolted). During the first tests at the low seismic intensity no damage of the panels appeared, but the cycles were already quite large, showing a dissipative. Figures 10 and 11 show the hysteresis cycles of both panels at the low seismic intensity.

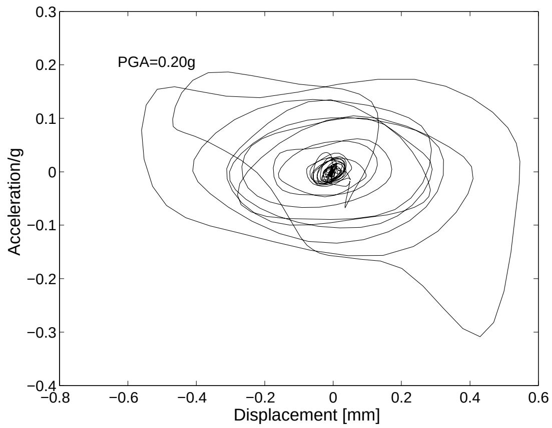

Figure 10 – Bolted panel: hysteresis at low level of the seismic intensity.

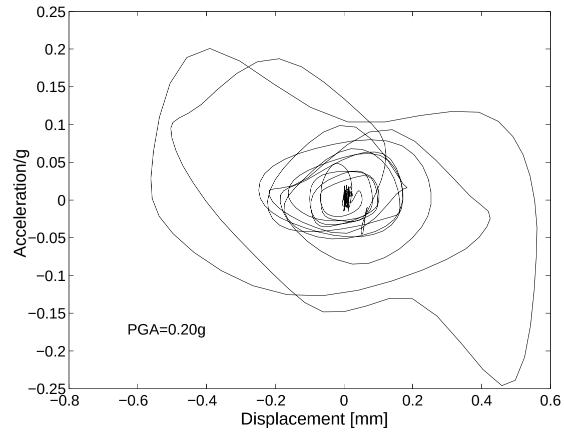

Figure 11 – Brazed panel: hysteresis at low level of the seismic intensity.

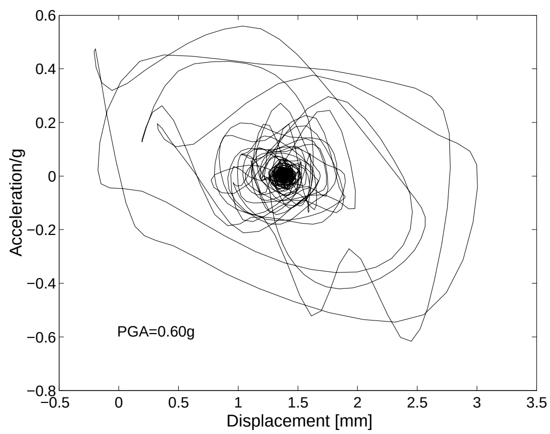

Figure 12 – Bolted panel: hysteresis at medium level of the seismic intensity.

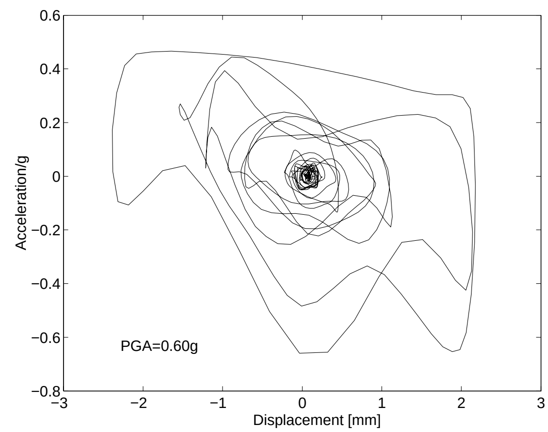

Figure 13 – Brazed panel: hysteresis at medium level of the seismic intensity.

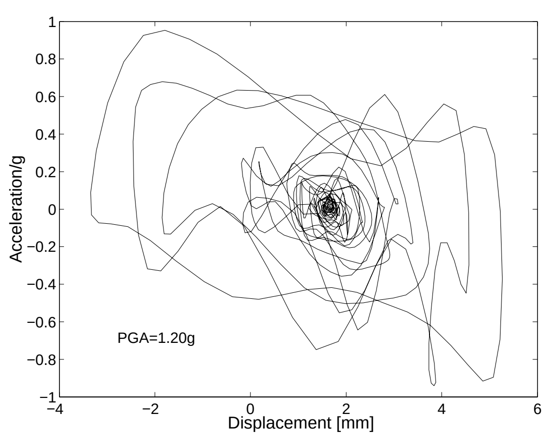

Figure 14 – Bolted panel: hysteresis at high level of the seismic intensity.

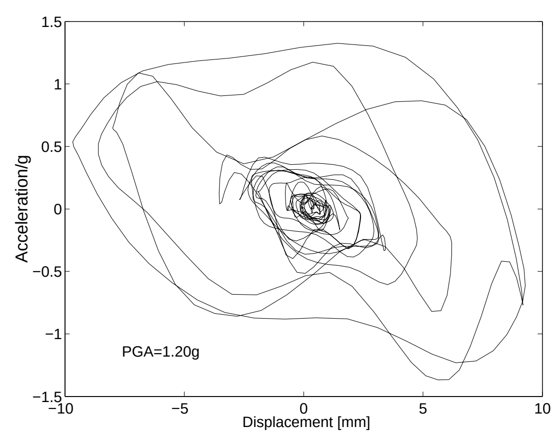

Figure 15 – Brazed panel: hysteresis at high level of the seismic intensity.

Increasing the PGA, the hysteresis cycles became wider, the dissipated energy was higher, and the panel did not lose its initial stiffness. From the comparison of hysteresis cycles of the bolted and brazed panels it can be noticed that the cycles are similar in shape and in size at low PGA.

At higher seismic level, the bolted panels showed some buckling phenomena, in particular the out-of-plane inflection started at PGA=0.5g (Figures 12,13, 14 and 15).

The brazed panels have been subjected to the same deformation only at high level of PGA because of the presence of the lateral stiffeners on the wings. Two transducers were located to measure the displacement orthogonal to the input direction of the panel corresponding to the out-of-plane deformation. Figures 16, 17, 18 and 19 show the out-of-plane displacement of the panels due to Aigio earthquake record. Each repetition of the signal produced an increment into the permanent deformation in both panels.

It can be noticed that the permanent deformation and the consequent loss of planarity of the panels, verified at the medium-high earthquake intensities, do not seem to affect their dissipative capacity.

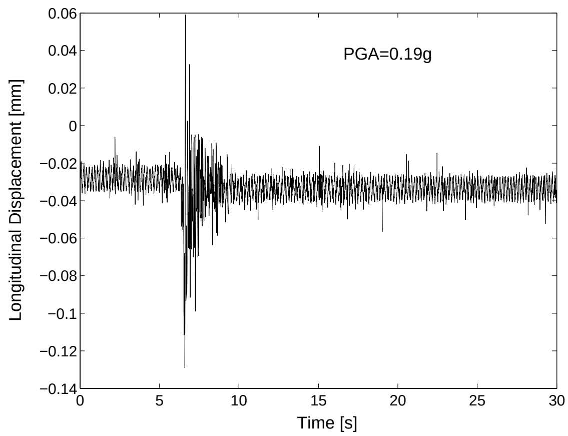

Figure 16 – Out-of-plane displacement of the bolted panel at low level of the seismic intensity.

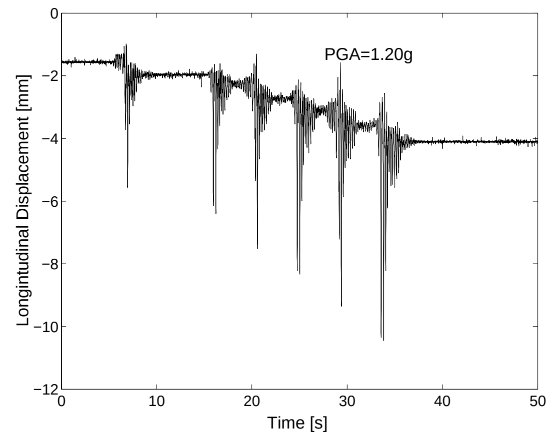

Figure 17 – Out-of-plane displacement of the bolted panel at high level of the seismic intensity.

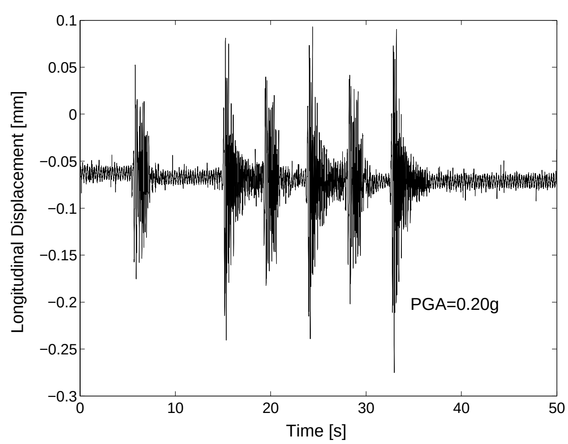

Figure 18 – Out-of-plane displacement of the brazed panel at low level of the seismic intensity.

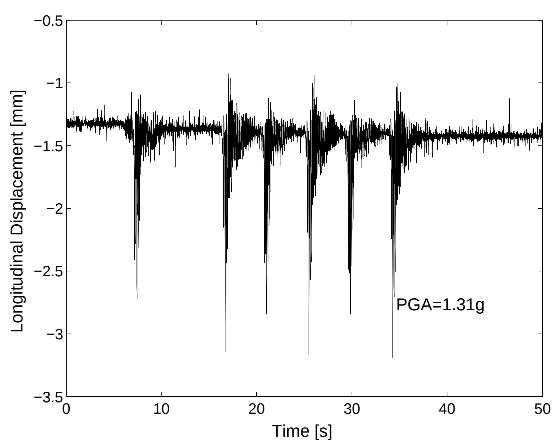

Figure 19 – Out-of-plane displacement of the brazed panel at high level of the seismic intensity.

Moreover, the wings added to the brazed panels reduced the out-of-plane deformation and assured a better cohesion between the plates but reduced the plasticization, and consequently the dissipative capacity of the brazed panels, that is effective at high level of the seismic intensity. Figure 7 shows the final deformed configuration of the bolted panel at the end of the test, a clear out-of-plane deformation is registered.
In Figure 20 the maximum displacement at the top of the frame column is reported versus to the PGA of the input. At low level of the seismic intensity, the frame with both the types of devices had obviously smaller displacements compared to the ones of the bare frame. For medium level of the input intensity the bolted panels introduced into the frame gave a better response with a reduced displacement at the top of the column, while at high level of 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 can be the design of this type of shear panels, 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. Figures 19 and 20 show respectively the displacement and acceleration time histories: of the frame with bolted panels at a PGA=0.20g, of the frame with two brazed panels at a PGA=0.20g, and of the bare frame at PGA=0.15g. The added damping, 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.

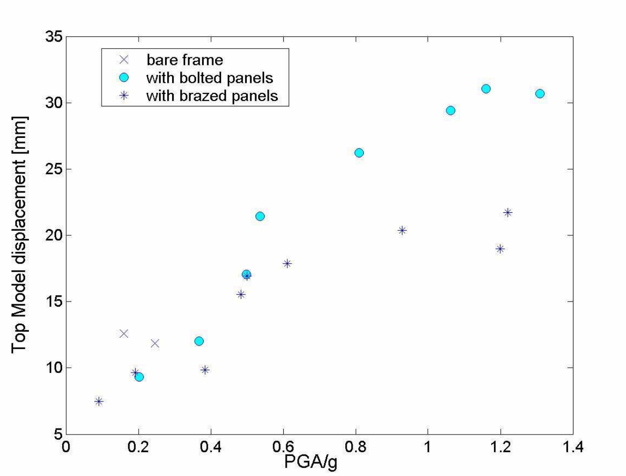

Figure 20 – Maximum transverse displacements of the top of the frame at increasing PGA.

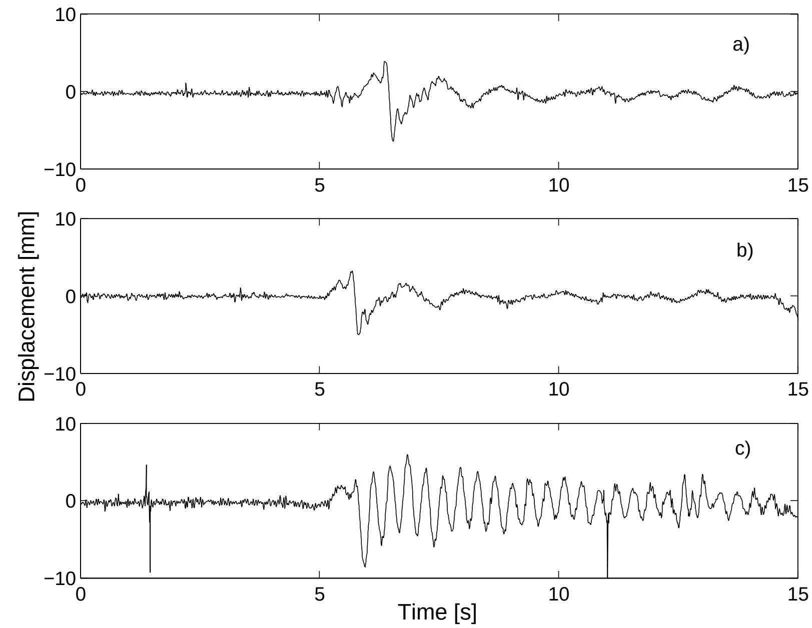

Figure 21 – Displacement at the top of the column of: a) frame with bolted panels PGA=0.20g, b) frame with brazed panels PGA=0.20g; c) bare frame PGA=0.15g.

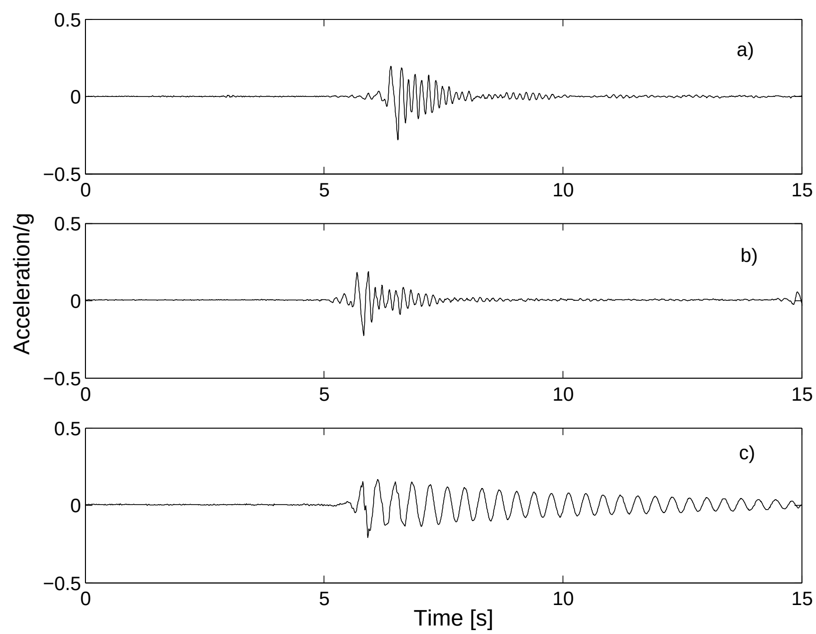

Figure 22 – Acceleration at the top of the column of: a) frame with bolted panels PGA=0.20g, b) frame with brazed panels PGA=0.20g; c) bare frame PGA=0.15g.

CONCLUSIONS

The performed tests on a frame protected with the proposed aluminium shear panels have shown their capability to dissipate a large amount of seismic energy, limiting and concentrating the damage. In fact, the tested frame was found to withstand even catastrophic events without damage. The localized damage was exclusively concentrated in the panels. This simple device has the advantage of an easy replacement that allows restoring rapidly the functionality of a building.

Two types of dampers have been tested on the shaking table. The comparison of the experimental results has shown that the total behaviour 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 guarateeing better cohesion of the plates, but they negatively influenced the plasticization capacity, since this inelastic phenomenon appeared at high level of the seismic intensity.

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

The test results have 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 level of the input seismic intensity. To solve these problems in the damper design the choice of the stiffeners, the type of connection among the plates and the plate thickness are crucial points.

ACKNOWLEDGEMENTS

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