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Experimental Tests on Steel Buckling Inhibited Shear Panels

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Abstract: Passive protection systems based on the use of metal shear panels represent an effective way for achieving a significant improvement of the seismic response of buildings. Nevertheless, the dissipative capacity of these devices could be limited by buckling phenomena. In order to reduce the influence of instability, "Buckling Inhibited Shear Panels" have been recently introduced as an innovative and convenient solution. It is based on the use of steel plated elements able to restrain out-of-plane displacements of the basic shear plate but without any type of interactions in terms of membrane strains. In this paper the outcomes of an extensive experimental campaign on the proposed system are shown. The tested coupons are made of steel and are characterized by two different thicknesses. Moreover, two technologies for the inhibition of buckling phenomena are examined. The former is able to contain the out-of-plane displacements for the only plate portions that are most involved in the development of the first critical modes. The latter, with a more complex assemblage of the parts, is obtained by inhibiting the out-of-plane deformations of the whole system. The results obtained, compared to the ones given by only steel plates without buckling restraining devices, allow to highlight the increase in terms of energy dissipation capacity that is possible to achieve through the proposed technologies, also evidencing some critical issues that can arise when little accuracy in the assembly of the system is spent.

Keywords: Buckling inhibited shear panels, dissipative device, experimental analysis, metallic dampers, seismic protection, shear panels, shear walls.

1. INTRODUCTION

Metal shear panels constitute a suitable high-performance technology for the seismic protection of both steel and reinforced concrete buildings. Since the beginning of the 70s such systems have been widely investigated with the purpose of defining the main structural features and behavioural aspects. This has allowed to reach an adequate knowledge, with particular regard to the stiffening capacity that they are able to offer, as well as to the significant ductility and dissipation capacity induced to the frames in which they are applied [1]. Guidelines for their design are currently given in the most advanced codes of North America [2-4] and Asia [5-7], allowing a large worldwide employment for the erection of a significant number of buildings.

One of the main issues related to the use of metal shear panels for moment resisting frames, in particular when they are characterized by a limited thickness, concerns the development of buckling phenomena. In fact, in such cases a detriment of the inelastic response, under alternating forces, is caused by pinching effects on the hysteretic cycles. This entails a reduction of the energy dissipation capacity of the entire system and consequently a larger engagement of the main structural members, such as beams, columns and connections.

In order to minimize the potentiality of the above degrading phenomena, as an alternative to the adoption of significant thicknesses of the base plate, which would lead to solutions that are not economically convenient and usually not complying the capacity design criteria, multi-stiffened thin plates have been proposed in last decades. These are conceived so that transversal and longitudinal stiffeners are properly arranged on the base plate with the task of reducing its free buckling length and, therefore, to postpone in the field of large deformations the occurrence of any instability.

Such solutions are often conjugated to the adoption of metallic low yield strength materials, which, apart from allowing to have instabilities for very high ductility demands, are characterized by significant deformation capacity [8]. Such an approach allowed to obtain shear panels characterized by a huge amount of damping capacity [9-13], comparable or even superior to the one of the most frequently used dampers, such as BRB (Buckling Restrained Braces) [14], friction and viscous devices.

Alternatively to the use of stiffeners, an innovative system has been recently proposed by the authors, indicated as "Buckling Inhibited Panel" (BIP), in which the mitigation of buckling phenomena is get through the use of steel elements which are arranged parallel to the base plate but are disconnected from the latter in order to restrain only the out-of-plane deformations of those parts of the panel that may be involved in buckling. The results of the first pilot tests, carried out by the authors on aluminium shear plates [15], have shown that, when compared with the more traditional stiffened plates, this solution leads to optimal dissipative capacities, characterized by large and full hysteretic cycles. Moreover, it has been observed that the proposed innovative solution ensures a better behaviour in terms of initial stiff-

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ness, which, for panels with welded stiffeners, is negatively influenced by the imperfections due to the development of shrinkage effects.

With the purpose of deepening the knowledge on the BIP system, the present paper provides the main outcomes of an experimental campaign recently carried out on thin steel shear panels characterized by different thicknesses and different buckling inhibition technologies. Particular attention is devoted to those detrimental effects that could jeopardize the system response when the plates are so thin that the gap between the inhibiter and the inhibited parts become really influencing. In fact, these negative phenomena were not recorded during the pilot tests, due to the fact that a particular care was spent for their minimization during the assemblage of the experimental specimens.

2. THE EXPERIMENTAL TESTS

Steel shear panels made of S275 steel and characterized by a square shape of 500x500 mm have been placed inside a steel articulated frame with pinned-end beams obtained by coupling two UPN 140 section profiles. Two thicknesses of 0.8mm and 2.5mm have been considered for the base plate.

Friction bolted connections have been designed for jointing the metallic plate to the frame, in order to avoid undesirable premature failure phenomena (bearing stress of the sheet or shear failure of the bolts) capable of compromising the cyclic response of the whole panel.

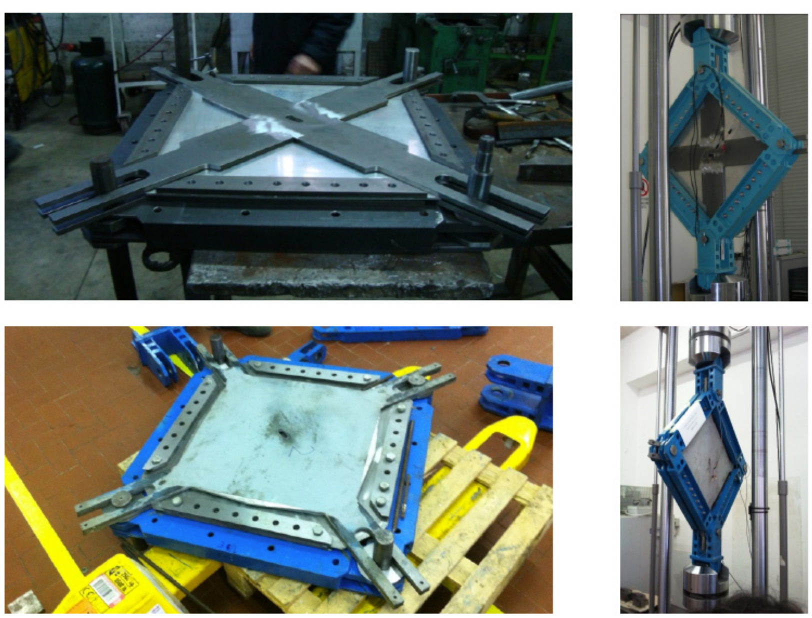
In order to prevent shear buckling of the base plate by restraining out-of-plane displacements, two different solutions have been proposed. The first solution represents a ‘‘partially’’ BIP (p-BIP), conceived in order to restrain the first four critical modes of the base plate. It has been obtained (see Fig. **1a**) by arranging two cross shaped steel elements, having a thickness of 10 mm and a width of 140 mm, at both sides along the diagonals of the plate. These elements have been characterized by fork-shaped slotted end connections centred on the hinge of the external articulated frame in order to do not develop membrane forces when loading the main system. Moreover, in order to reduce the friction between the base plate and the cross shaped elements, a sheet of lexan has been glued to their internal sides. It is to be pointed out that the partial buckling inhibition devices allow some secondary buckling phenomena developing along the medians of the triangular not restrained portions of the base plate.

The second solution produces a ‘‘totally’’ buckling inhibited panel (t-BIP). In fact it has been conceived in order to restrain possible out-of-plane displacements of the entire base plate. The external devices, constituting the restraining system, are two octagonal shaped steel plates, which are characterized by a thickness of 10 mm and are able to cover almost the entire base sheeting (Fig. **1b**).

Also in this case, lexan has been employed in order to reduce the friction between the parts. In addition slotted end connections have been used to accommodate in-plane movements of the buckling inhibiting plates.

Totally, the following six full-scale specimens have been considered:

- StSP8: 0.8 mm thick steel shear panel;
- p-BIP St8: 0.8 mm thick steel partially Buckling Inhibited Panel;
- t-BIP St8: 0.8 mm thick steel totally Buckling Inhibited shear Panel;
- StSP25: 2.5 mm thick steel shear panel;
- p-BIP St25: 2.5 mm thick steel partially Buckling Inhibited Panel;
- t-BIP St25: 2.5 mm thick steel totally Buckling Inhibited shear Panel.



a)

b)

Fig. (1). Tested devices: (**a**) Partially Buckling Inhibited Panel (p-BIP) and (**b**) totally Buckling Inhibited Panel (t-BIP).

It is to be highlighted that the used testing apparatus has been initially designed for a 5 mm thick pure aluminum shear panel which, as referred before, have been used in order to carry out pilot tests. The smaller thickness of the tested steel plates led to have a larger gap (about 4.0 mm for the thinner coupons and 2.5mm for the others) between the inhibition and the base plate. On the other hand, it must be underlined that the restraining plates have been designed in order to contrast the out of plane deformation of the aluminium plates without excessive deformation. Also from this point of view, the fact of having adapted this system for specimens made of another material has led to some counter-indications.

All the tested panels have been diagonally loaded through a MTS810 machine, following the cyclic quasi-static protocol provided by ECCS-CECM [16]. This takes into account a procedure based on some cycles in the elastic range and then on three repetitions for progressively increasing displacement amplitudes, defined as integer multiples of the displacement corresponding to the material yielding.

The applied force has been measured by the loading cell of the tested machine, whereas the diagonal displacement of tested panels has been measured by a mechanical diagonal transducer. In addition, four mechanical transducers have been placed on the perimeter of the panel, measuring the possible relative movements between the panel edges and the elements of the perimeter frame.

3. THE EXPERIMENTAL RESULTS

3.1. Thinner Shear Panels (0.8 mm)

The hysteretic responses of the tested specimens "StSP08", "p-BIP St08" and "t-BIP St08" are shown in (Fig. **2**) in terms of shear stress-shear strain relationships.

It can be noticed that the not inhibited shear panel "StSP08" presented relevant pinching effects already for a shear strain of 0,66% (3mm of diagonal displacement). On the other hand, buckling phenomena have been observed also for protected devices, namely the panels "p-BIP St08" and "t-BIP St08". In fact, in these cases, the used restraining steel elements have not been completely effective in avoiding the development of buckling, due to the relative relevance of the gap between the plates and the inhibition devices with respect to the small thickness of the firsts.

As a consequence, pinching effects have been observed also on the hysteretic cycles of both restrained panels for low shear strain demands. Moreover, it is evident that the dissipative response retrieved for these two panels is almost the same (Figs. **3a** and **3b**). This means that when very thin shear plates are used, their response is fundamentally affected from the firsts buckling modes. On the other hand, it has been observed that the inhibition devices were able to contrast the out-of-plane displacements of the buckling waves when these attained a certain amplitude, thus retrieving back larger hysteretic cycles with respect to the bare plate "StSP08". This confirms that the inhibiting action could have a certain level of effectiveness also in presence of the above technological criticalities. This aspect is also evident by analysing the panels response in terms of equivalent viscous damping (Fig. **3c**) which, for the buckling inhibited panels, is almost 30% when shear strains higher than 4% are attained, whereas the same parameter is about 20% for the "StSP08" panel.

The analysis of other performance parameters permits to put in evidence that the application of the buckling restraining devices allowed to retrieve higher stiffness (Fig. **3d**) and hardening ratio (Fig. **3e**), in particular for the "t-BIPSt08" specimen, which, nevertheless, presented a quicker degradation of the normalized strength for a shear strain of 9%, when collapse phenomena propagated significantly in the centre of the plate.

The experimental evidences observed during the tests of 0.8 mm thick plates are synthetically listed in Table **1**. A linear elastic behaviour up to a shear strain of ± 0.11% has

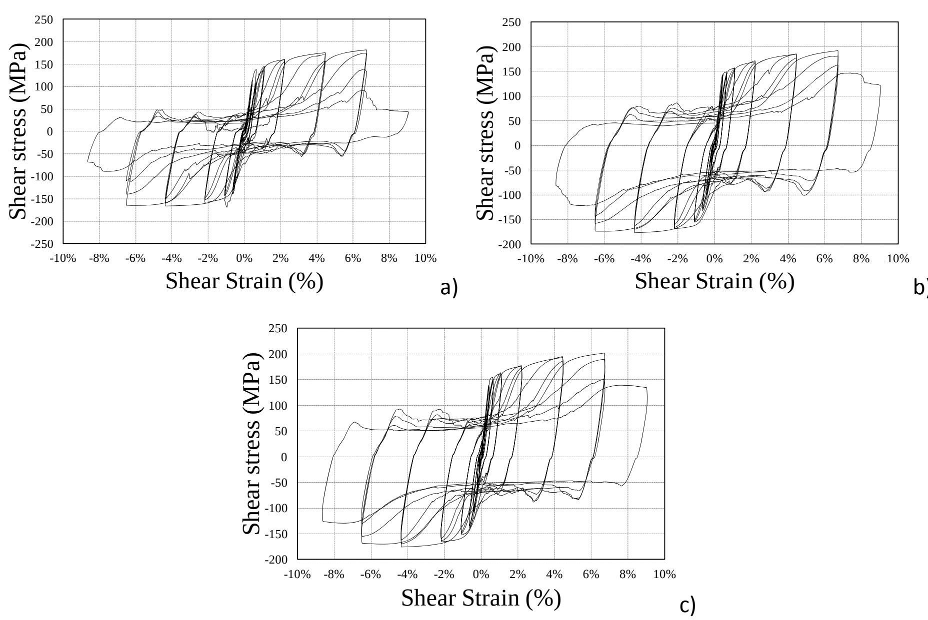


Fig. (2). Hysteretic cyclic response of **a**) "StSP 08", **b**) "p-BIPSt08", **c**) "t-BIPSt08".

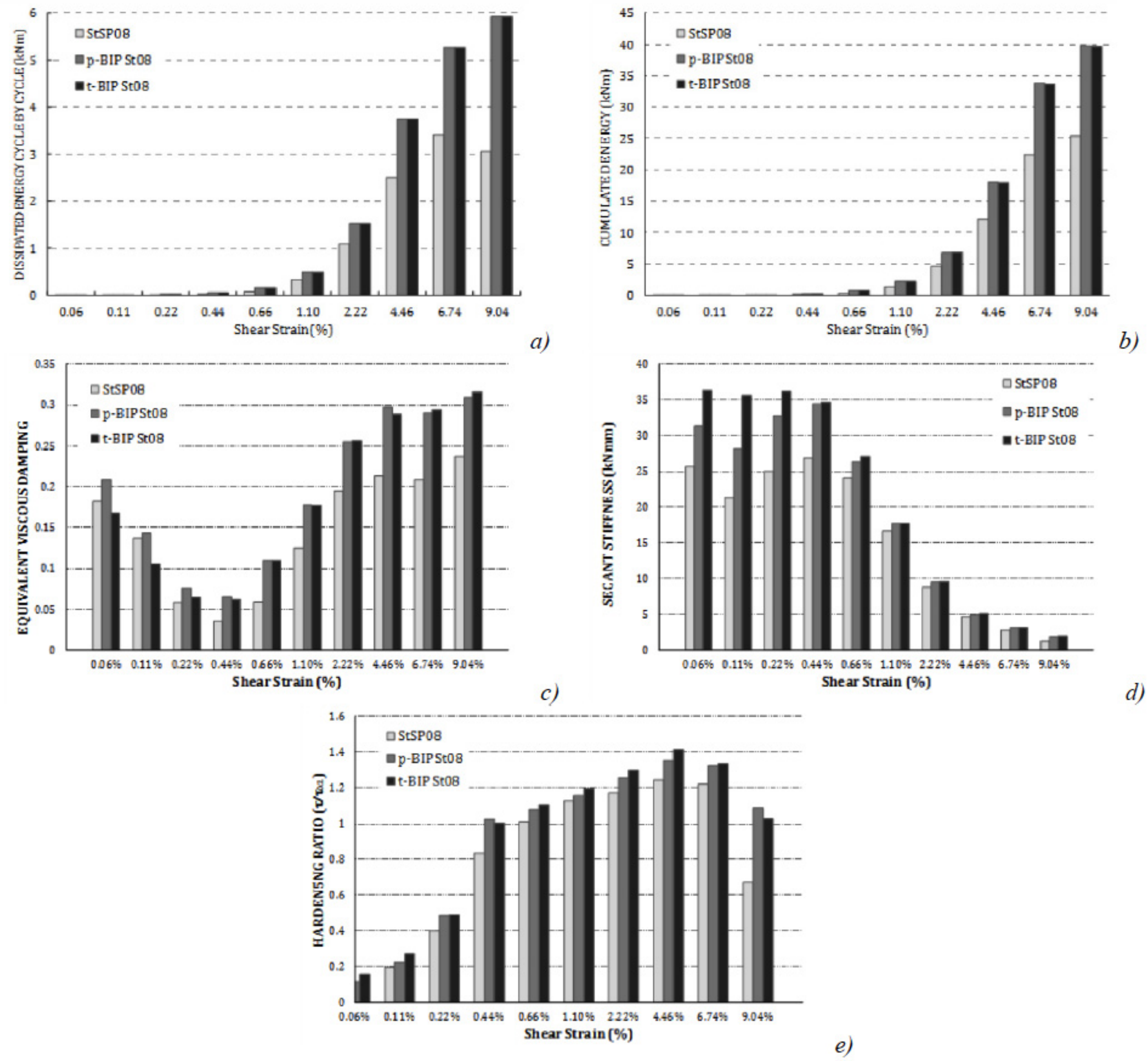


Fig. (3). Comparison between “StSP08”, “p-BIPSt08” e “t-BIPSt08” in terms of: **a**) dissipated energy by cycle, **a**) cumulated dissipated energy, **e**) equivalent viscous damping, **d**) secant stiffness, **e**) hardening ratio.

Table 1. Experimental evidences (0.8mm shear panels).

Shear strain range (diagonal displacement)	St 08	p-BIP St 08	t-BIP St 08
[0, ±0.11%] ([0, ±0.50 mm])	Elastic behaviour		
[±0.11%, ±0.66%] ([±0.50 mm, ±3.00 mm])	Buckling phenomena with the development of pinching effects	Inelastic behaviour without buckling phenomena	
[±0.66%, ±2.20%] ([±3.00 mm, ±10.00 mm])	Fully development of tension field mechanisms	Development of buckling waves in contact with the inhibition system	Plastic deformations of the panel parts
[±2.20%, ±4.40%] ([±10.00 mm, ±20.00 mm])	Panel Damage closed to the perimeter members	Panel damage closed to the inhibition system	Panel Damage at the vertexes of the plate
[±4.40%, ±9.04%] ([±20.00 mm, ±40.00 mm])	Detachment of the plate from the connection system up to the collapse of the specimen	Plate tears closed to the inhibition system with buckle waves pushing on the restraining elements	Plate tears in the centre of the panel with buckle waves strongly pushing on the restraining elements

been noticed. After this threshold “StSP08” presented the first buckling phenomena with pinching effects on the hysteretic cycle.

For the same deformation levels, the buckling inhibited panels, “p-BIPSt08” and “t-BIPSt08” provided first inelastic behavior, even if buckling phenomena were not noted up to a shear strain of ± 0.66%. Starting from this demand, also the inhibited panels evidenced some local instabilities, as shown in (Fig. **4**), where the state of the tested specimens and the relative hysteretic cycles are represented for a shear strain demand of 1.10%.

When a shear strain of ±2.20% was reached, the “StSP08” specimen developed the typical behaviour of slender panels, characterized by a tension field mechanism (Fig. **5a**), while instability patterns of the not inhibited plate portions of “p-BIPSt08” were more evident (Fig. **5b**), with buckled waves fully in contact with the restraining devices, whereas, any particular new phenomena have been not registered for the “t-BIPSt08” specimen (Fig. **5c**).

For a shear strain of ±4.40%, the first damage on the base plate has been observed. For the not-inhibited steel panel “StSP08”, fractures have been noted closed to the perimeter members of the frame (Fig. **6a**), while, for the “p-BIPSt08” shear panel, same tears concentrated in the proximity of the inhibition systems have been evidenced (Fig. **6b**). Finally for the “t-BIPSt08” (Fig. **6c**) specimen, ruptures have been observed at the vertexes of the plate.

For larger shear demands, the failure of the plate develops more and more, provoking the complete detachment of the shear plate of the “StSP08” from the elements of the perimeter frame, tearing around the diagonals of the “t-BIPSt08” panel, and both such phenomena for the plate of the “p-BIPSt08” specimen. For the latter two panel types, it has been also noted that the plate buckling waves in contact with the external restraining plate provoked out-of-plane deformations of this devices. These deformations, however, resulted to be elastic, as they were recovered after the system disassembling. In Fig. (**7**), the final states of the tested specimens are shown.

3.2. Thicker Shear Panels (2.5 mm)

In Fig. (**8**) the hysteretic cycles of the tested 2,5mm tick specimens are illustrated. Also in this case, some buckling phenomena have been noticed even for the buckling

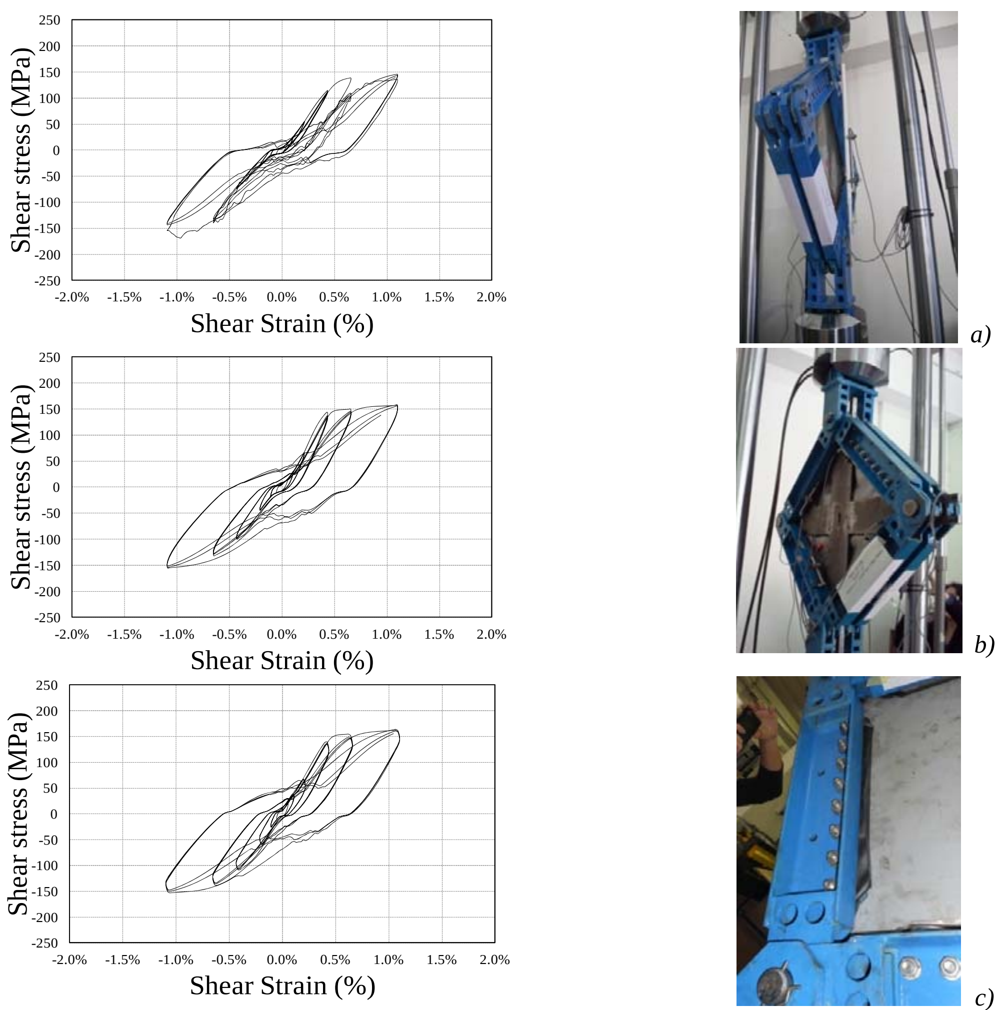


Fig. (4). Hysteretic behavior and experimental evidences: **a**) “StSP08”, **b**) “p-BIPSt08” and **c**) “t-BIPSt08” shear panels (shear strain of 1.10%).

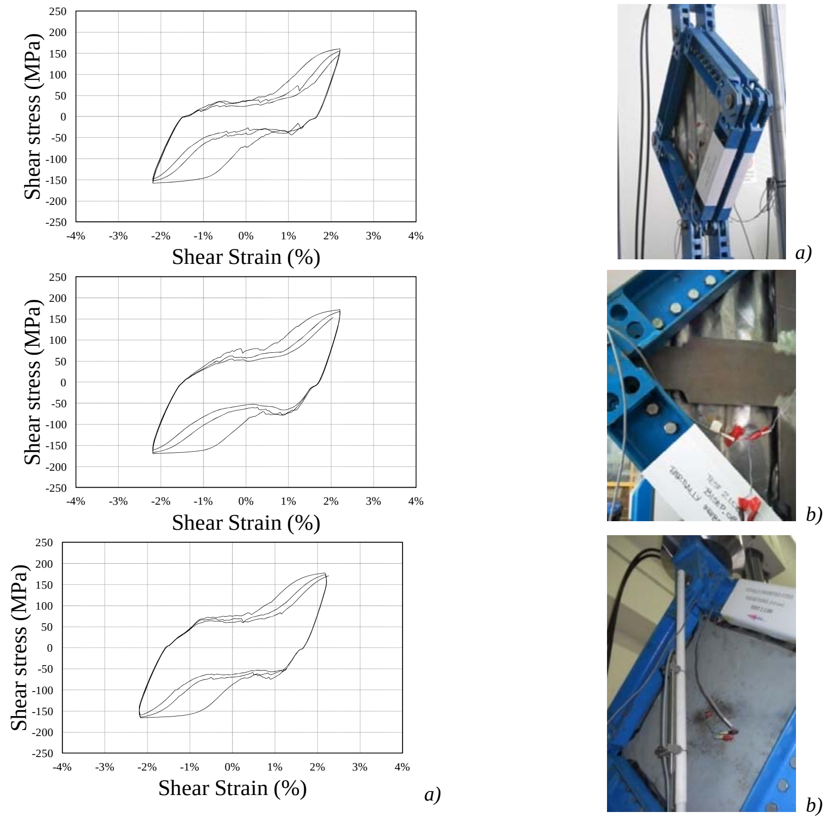


Fig. (5). Hysteretic behavior and experimental evidences: **a**) "StSP08", **b**) "p-BIPSt08"and **c**) "t-BIPSt08" shear panels (shear strain of 2.20%).

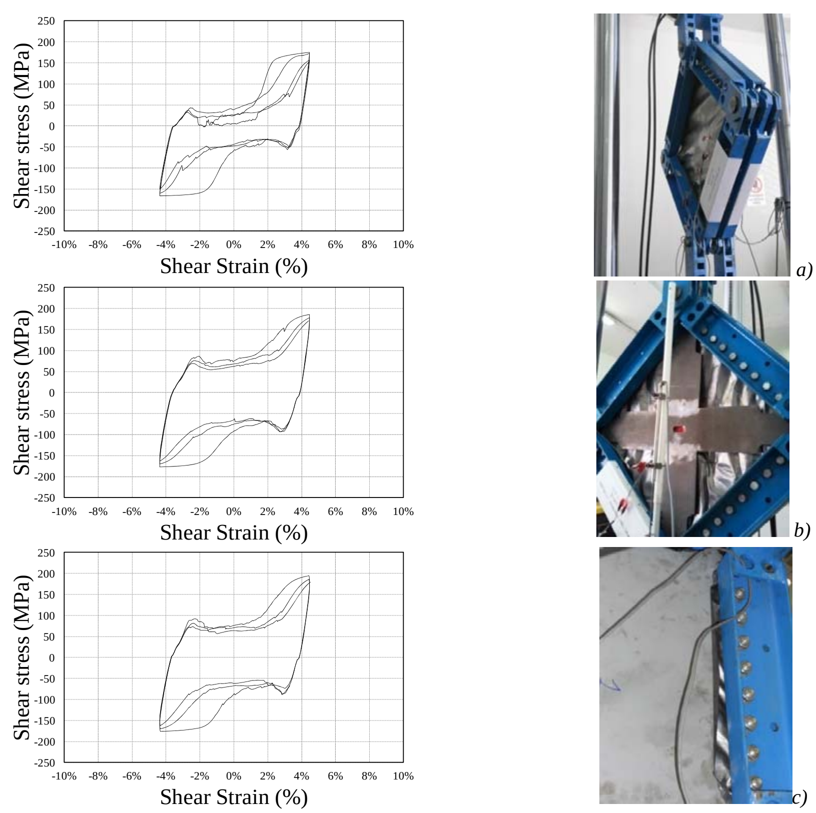


Fig. (6). Hysteretic behavior and eperimental evidences: **a**) "StSP08", **b**) "p-BIPSt08"and **c**) "t-BIPSt08" shear panels for (shear strain of 4.40%).

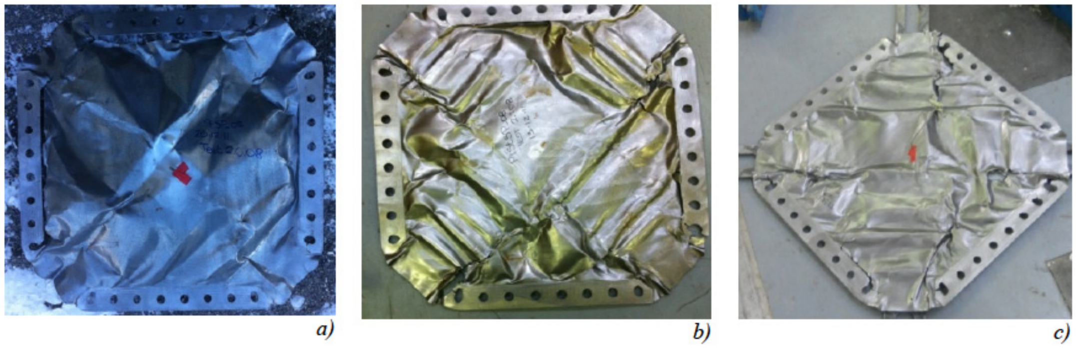


Fig. (7). Collapse mechanisms observed on the plates: **a**) "StSP08", **b**) "p-BIPSt08"and **c**) "t-BIPSt08" shear panels (shear strain of 9.04%).

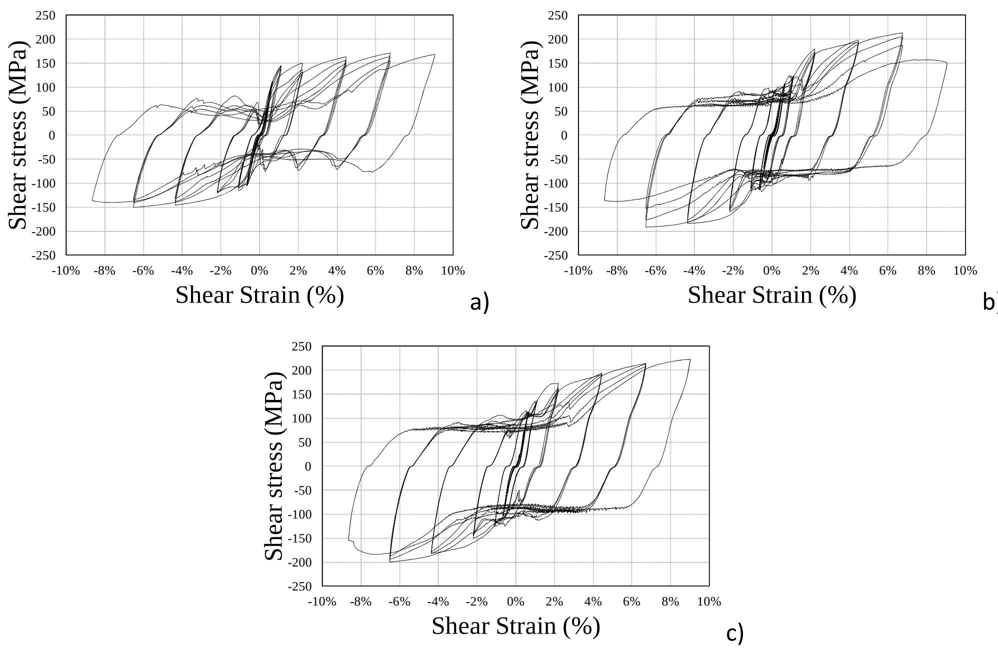


Fig. (8). Hysteretic cyclic response: **a**) "StSP 25", **b**) "p-BIPSt25", **c**) "t-BIPSt25".

inhibited panels. Nevertheless, the reduced gap between the restraining and the restrained plates has entailed that the detrimental effects due to pinching resulted less important than the ones registered for the 0.8 mm thick panels, with hysteretic cycles significantly larger. Moreover, in this case, an appreciable difference between the cyclic response of the "p-BIPSt25" and the "t-BIPSt25" can be observed, the first resulting more degraded.

The above remarks are also confirmed by the analysis of the global behaviour parameters shown in Fig. (**9**). The energy per cycle dissipated by the "t-BIPSt25" specimen is 1.3 times the one of panel "p-BIPSt25". Moreover, in this case, the decay of strength observed for the totally buckling inhibited panel, when very high shear strain demands are attained, has not been observed.

The experimental evidences observed during the tests are presented in Table **2**. It is indicated that the systems remained elastic up to a shear strain of about 1%. Beyond this limit, for example for a shear strain of 2.2%, the bare plate shear panel "StSP 25" presented the first significant buckling phenomenon (Fig. **10.a**). It has been also noticed that, at this stage, the restraining devices presented some evident out-of-plane deformations due to the trust action of the plate which tended to buckle (Figs. **10.b**). Such a phenomenon led the restraining plates to move toward each other at their ends creating additional contacts (Figs. **10.c**). It is evident that this type of behaviour was due to the fact that the shear plates were characterized by a higher shear strength with respect to the pure aluminium panels for which the whole system was designed. Then, one can gather that the fact of having employed not sufficient restraining plates influenced the panel response. This is evident by the analysis of the hysteretic cycles which presented some horizontal bevelled branches that reduced, in a significant way, the panel response for low shear strain demands.

First plate tearing on the not-inhibited shear panel "StSP 25" have been observed close to the boundary steel frame, for a shear deformation of ±4.40%, while, concerning the buckling inhibited panels, some failures concentrated close to the connection system.

The collapse of the devices have been observed for a shear strain of ±9.04%. For the not inhibited shear panels, failure was concentrated at the centre of the plate, whereas, for the "p-BIPSt25" and "t-BIPSt25", ruptures of the

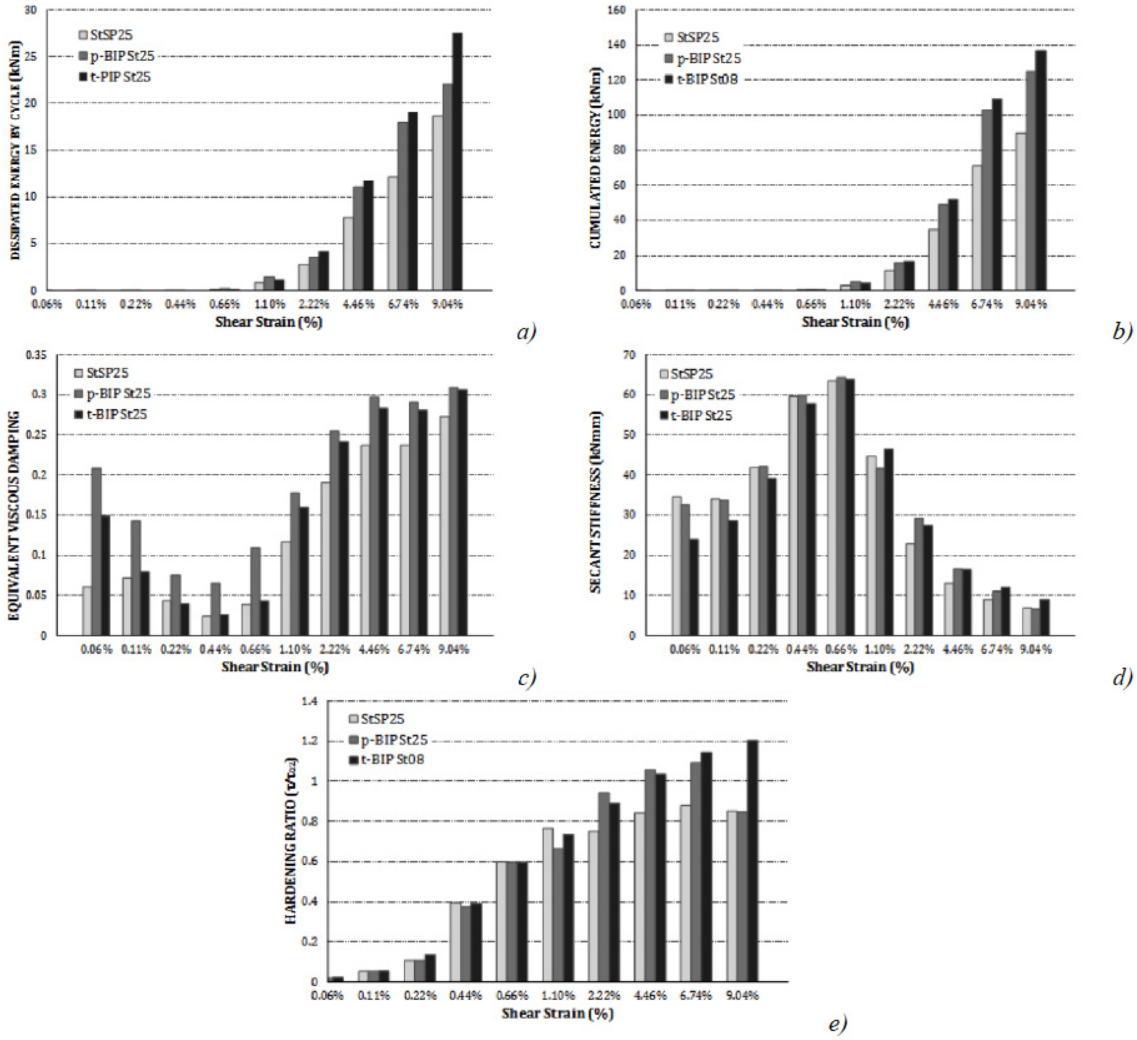


Fig. (9). Comparison between "StSP25", "p-BIPSt25" and "t-BIPSt25": **a**) dissipated energy by cycle, **b**) cumulated dissipated energy, **c**) equivalent viscous damping, **d**) secant stiffness, **e**) hardening ratio.

Table 2. Experimental evidences (2.5 mm shear panels).

Shear strain range (diagonal displacement)	St 25	p-BIP St 25	t-BIP St 25
[0, ±0.11%] ([0, ±0.50 mm])	Elastic behaviour		
[±0.11%, ±1.10%] ([±0.50 mm, ±5.00 mm])	First out of plane deformations	Elastic behaviour	
[±1.10%, ±2.20%] ([±5.00 mm, ±10.00 mm])	First buckling phenomena; development of pinching effects	Elastic deformation of the inhibition devices; Development of slight pinching phenomena on the hysteretic cycle	Development of slight pinching phenomena on the hysteretic cycle
[±2.20%, ±4.40%] ([±10.00 mm, ±20.00 mm])	Tension field developing	Panel damage closed to the connection system	Panel damage closed to the connection system
[±4.40%, ±6.74%] ([±20.00 mm, ±30.00 mm])	Plate tearing closed to the perimeter frame and on the plate diagonal	Panel damage close to the restraining plate	Panel damage closed to the restrain-ing plate
[±6.74%, ±9.04%] ([±30.00 mm, ±40.00 mm])	Collapse of the system	Collapse of the system	Collapse of the system

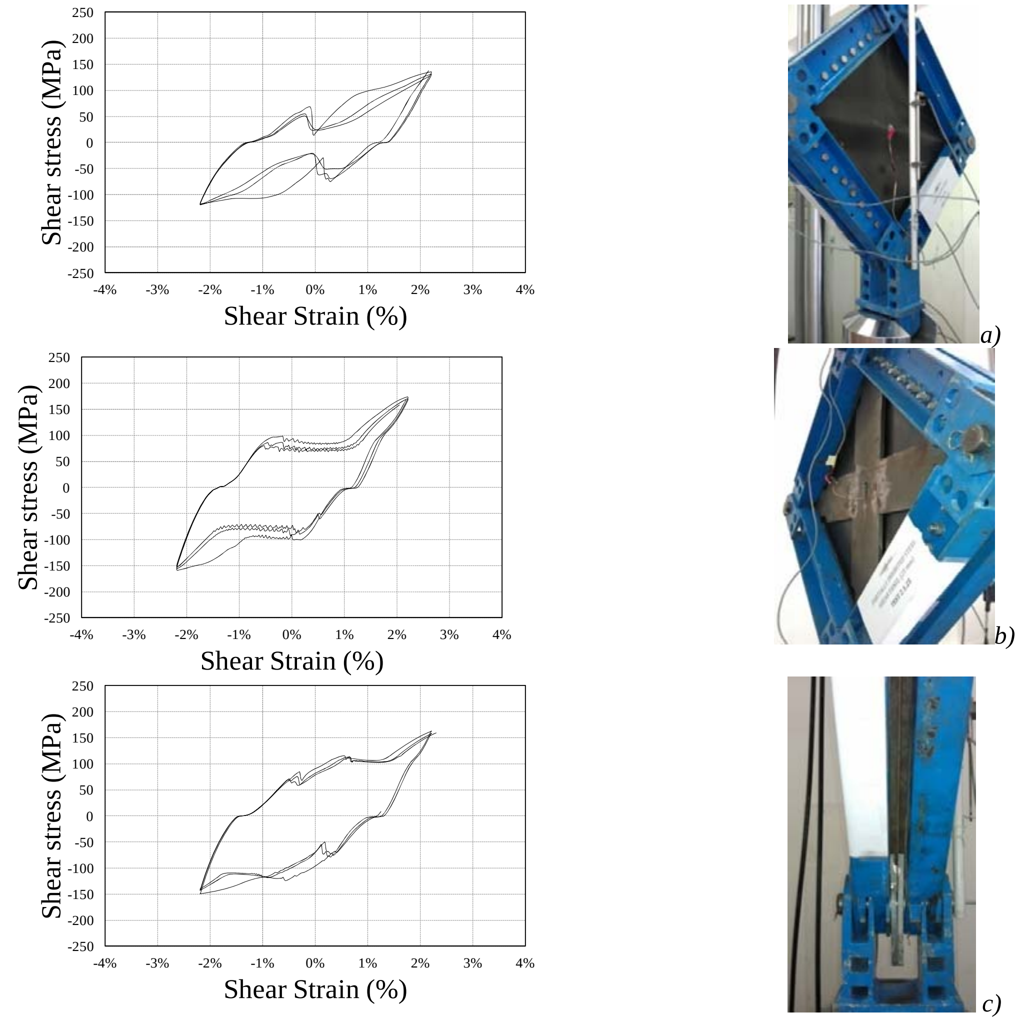


Fig. (10). Hysteretic behaviour and experimental evidences: **a**) "StSP25", **b**) "p-BIPSt25"and **c**) "t-BIPSt25" shear panels (shear strain of 2.20%).

Fig. (11). Collapse mechanisms observed on the plates: **a**) "StSP25", **b**) "p-BIPSt25"and "**c**) t-BIPSt25" shear panels (shear strain of 9.04%).

perimeter connection system occurred (Fig. **11**). This last phenomenon was very surprising as the connection system was designed in order to work for friction. The justification was given, according to the fact that the thrust action of the restraining elements on the perimeter members of the frame unloaded the bolted connections which, therefore worked in shear providing not sufficient strength. It is also to be observed that at the end of the test the restraining plates presented significant inelastic deformations, thus resulting severely damaged, as it is shown in (Fig. **12**) for the two restraining elements of the "t-BIPSt25" specimen, which, evidently, lost their straightness (Fig. **12**).

CONCLUSION AND VISIONS

The presented experimental tests confirmed that buckling inhibited shear panels proposed by the author in [15] represent an innovative way to obtain effective dissipative devices for the protection of steel and reinforced concrete structures.

Nevertheless, the comparison of tested shear panels made of thin steel plates with the more efficient system made of pure aluminium thicker plate allows to outline some conclusive remarks about the counter-indications that can arise when the system is not well conceived, the material features of the base plate are not properly taken into account for the design of the system, as well as when proper tolerances are not used.

In particular:

- when buckling inhibited shear panels are designed, it is necessary to manage in a careful way the gaps, which could be particularly significant for very thin sheeting, between the restraining and the restrained parts. In fact, the response of the system for low-medium shear strain demands could be negatively affected by such a gap in terms of dissipative capacity.
- When the gap significantly influence the system response, the "p-BIP" solution is surely more convenient with respect to the "t-BIP" one. In fact, in this case, the restraining action on the panel portions that are sensitive to the higher critical modes is not necessary, as these do not influence the panel response.
- When larger thicknesses and smaller gaps are applied, the performance of the system could be negatively influenced by the out-of-plane deformability of the restraining elements, in particular when they are not properly designed according to the strength of the material of the base plate.

All the above conclusions suggest the development of further research activities. In particular, it will be necessary to understand which are the maximum acceptable gaps between the constituting parts and, therefore, to prescribe the tolerances that, depending on the plate thickness, are allowed in the production process. This aspect could be faced by developing appropriate sensitivity analyses by using FEM models calibrated on the basis of available test results. In addition, design provisions, concerning the determination of the correct out-of-plane stiffness that must be assumed for the restraining plates according to the expected shear strength of the base plate, should be provided.

Fig. (12). The inelastic deformations of the restraining plates of the"p-BIPSt25" specimen.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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