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BUCKLING INHIBITED METAL SHEAR PANELS: A NEW DAMPER BASED ON THE DEVELOPMENT OF THE BRB CONCEPT IN THE 2D SPACE

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Abstract

In the current paper, an innovative dissipative shear panel for seismic protection of steel and reinforced concrete buildings is dealt with. It represents an extension of the Buckling Restrained Brace concept in the bi-dimensional space, as it is based on the use of a metal plate, made of aluminum or steel, representing the core of a damper whose hysteretic response could be properly controlled by an external jacket able to inhibit either the most important or, even, all the buckling phenomena under shear forces.

The main results of an experimental campaign carried out under cyclic loads on both partially and totally Buckling Inhibited Shear Panels, made of different metallic materials and thicknesses, are analyzed and presented. Two different solutions are analyzed. The former is conceived in order that the buckling inhibition system restrains the out-of-plane displacements of the plate portions centered around the two diagonals, which are more sensible to the firsts and most important critical modes. The latter is based on devices able to restrain the out-of-plane displacements of the whole system.

The obtained results allow to observe the significant improvement of dissipative capacity that the buckling inhibition devices are able to provide. Nevertheless, it is pointed out that for reduced thicknesses of the base plate, the system performance could be jeopardized due to the gap between the inhibiting and the inhibited parts within which buckling phenomena could develop.

Keywords: Shear Panels, Steel plates, Shear buckling, Aluminum, Metallic Dampers, Seismic Protection.

1. Introduction

The concept of buckling inhibition for the manufacturing of metallic dampers has found a large consensus since the early nineties. Hence, several types of Buckling Restrained Braces (BRBs) were proposed and patented [1, 2, 3 and 4] with the result that, nowadays, these represent one of the most effective solutions used for new and existing constructions in earthquake prone zones. In fact, they are able to provide a profitable capacity to absorb the input earthquake energy already for low seismic demands and to dissipate it throughout suitable hysteretic mechanisms that are not significantly influenced by buckling detrimental effects [5].

Similarly, weak metal shear panels have been proposed in the last decades as dissipative devices for the seismic protection of buildings and bridges. Most of the proposed solutions have been conceived by using low yield stress point materials [6]: Nakashima proposed to use a steel type characterized by a low carbon content, whose 0.2 percent offset yield stress is 120 MPa [7]; De Matteis et al. [8-9] used an almost pure aluminum that, following a heat treatment process, is characterized by a conventional yield stress of 25 MPa and a ductility of about 40% [10]; besides, Rai et al. [11-12] profitably used miscellaneous aluminum alloys.

The great part of the existing studies on weak shear panels concerns relatively thin plates on which transversal stiffeners were applied in order to shift the activation of potential buckling phenomena in the inelastic field. However, ongoing research efforts are focusing on alternative solutions, such as the ones based on the application of perforations on the base plate in order to control the shear strength and to divert the internal stress state so that the arising of possible buckling phenomena is avoided [13-14].

Recently, the concepts of buckling inhibition and of dissipative shear panels have been combined in order to obtain an innovative type of damper, named as *Buckling Inhibited Shear Panels* [15]. It is made of a metal shear plate working in shear, representing the core of the system, whose out-of-plane deformations are restrained by means of external devices working as a jacket that do not interact with the plate when this is subjected to membrane strains.

In particular, two type of solutions have been proposed. The first, named *partially Buckling Inhibited Shear Panels*, is conceived in order that the inhibition system restrains only the parts of the base plate that are more sensible to the firsts and more important critical modes. On the contrary, the latter, named *totally Buckling Inhibited Shear Panels* is equipped with devices able to restrain the out-of-plane displacements of the whole system.

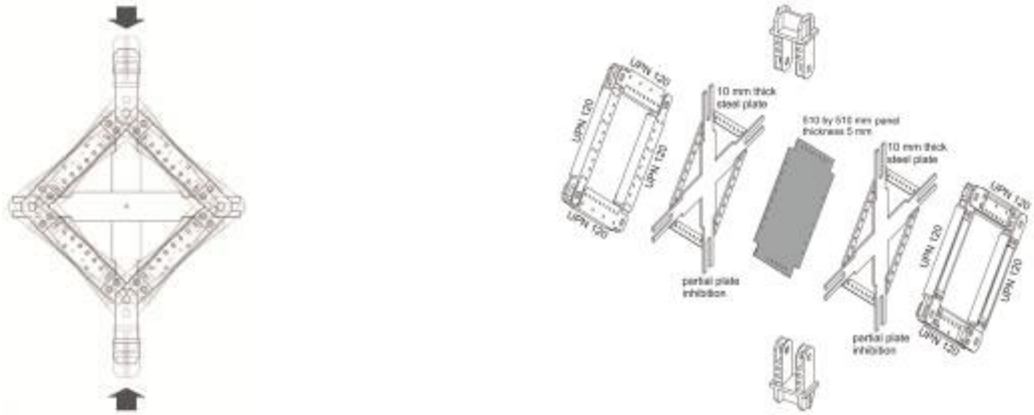
A wide experimental campaign in order to observe the cyclic performance of both the two technological solutions has been carried out. Firstly, the use of pure aluminum shear plates has been investigated. In this case the potentiality of the restraining system was enhanced by the possibility of controlling the panel strength by the use of a low stress point material which, moreover, is characterized by a large ductility. As a consequence, in this case, the necessity of realizing a weak system is not necessarily to be complied with the use of very thin sheeting. In a second stage, the experimental campaign has concerned a Buckling Inhibited Shear Panel typology characterized by the use of a more conventional material, namely a S235 steel. In this case, thinner plates have been used, with a more influential gap between the restrained and the restraining parts. As a consequence, the detrimental effects produced by this gap has been evidenced.

In this paper, the main results of the experimental campaign described above are reported. First, both the tested systems are described (Section 2). Then, in Section 3 the test results are provided and the experimental evidences are commented. Finally, some conclusive remarks concerning the technological issues to be faced in the manufacturing process of the proposed system are given.

2. The tested systems

2.1 Systems layout

In Fig. 1, the tested *partially Buckling Inhibited Shear Panel* and its constituting components are shown. It has been conceived so that the first fourth critical modes of the base plate (Fig. 2) are restrained. To this aim, two cross shaped steel elements, having a thickness of 10 mm and a width of 140 mm, have been arranged at both sides along the diagonals of the plate.



a)

Fig. 1. The studied partially Buckling Shear Inhibited Panel.

These elements have been characterized by fork-shape slotted end-connections centered around the hinge of the external articulated frame -connected to the base plate throughout tightened bolts in order to transfer the shear forces- so to do not develop membrane forces when loading the main system.

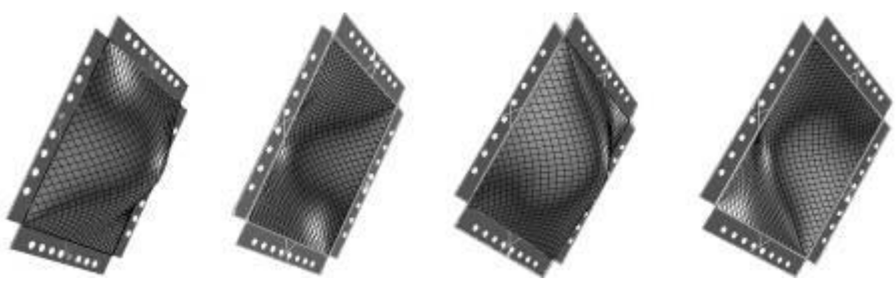


Fig. 2. First fourth critical modes for a square plate.

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 side. It must 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, shown in Fig. 3, represents a *totally Buckling Inhibited Shear Panel*.

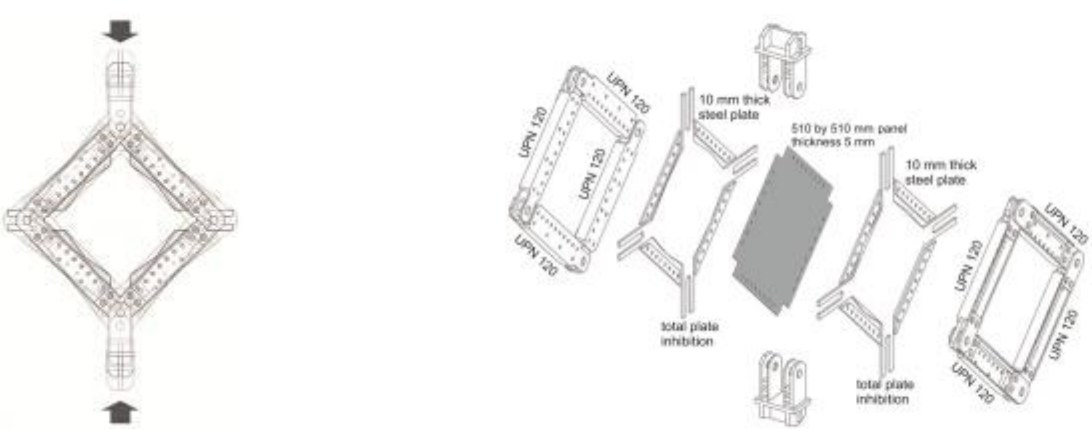
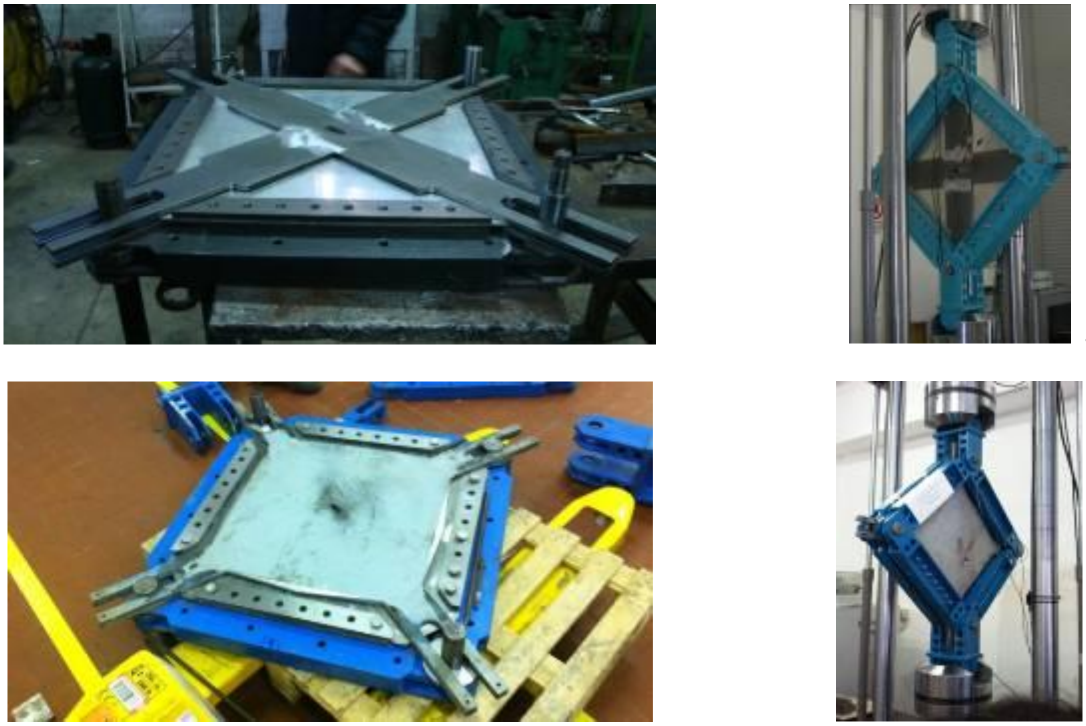


Fig. 3. The studied totally Buckling Inhibited Shear Panel.

As already stated, it is 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 plate. Also in this case, lexan sheeting have been employed in order to reduce the friction between the parts.

The two proposed devices are shown in Fig. 4 during the assemblage process and during one of the performed experimental tests.



a)

b)

Fig. 4. The two proposed dampers during the assemblage and the testing processes: (a) partially Buckling Inhibited Shear Panel and (b) totally Buckling Inhibited Shear Panel

It should be highlighted that the thickness of the buckling inhibiting system has been chosen on the basis of a previous numerical study of the authors [16]. Nevertheless, a proper design procedure of this device could be drawn only on the basis of more accurate models that are currently in the process of being calibrated starting from the experimental outcomes of the experimental study presented in this paper.

For both the tested shear panels, the internal plate has been positioned into a square articulated steel frame made of four rigid UPN120 built up members obtained by coupling two channel shaped profiles. The perimeter connections have been realized by 8.8 grade steel friction bolts with diameter of 14 mm and a pitch of 50 mm. Each bolt has been subjected to a controlled pretension force of 48.6 kN, that has been set up in order to get a friction strength higher than the shear demand, so to avoid sliding between the parts. In addition, in order to increase the contact area between the plate and the built up members, double sided internal 10mm thick plates (two for each side of the articulated frame) have been applied.

It is worthy of being noticed that the used additional devices are not welded, this permitting to annul the initial imperfections due to shrinkage which, contrarily, usually influence the performance of more conventional dissipative shear panels characterized by the presence of welded stiffeners.

2.2 The tested coupons

The experimental campaign has been carried out on six Buckling Inhibited Shear Plates characterized by different thicknesses and materials. These have been named as follows:

- p-PASP: 5.0 mm thick Pure Aluminum partially Buckling Inhibited Panel;
- c-PASP: 5.0 mm thick Pure Aluminum totally Buckling Inhibited 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;
- 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.

All the tested plates are characterized by a size of 500x500 mm and have been mounted on the articulated steel frame described in Section 2.1.

As for the mechanical features of the base material, the EN-AW-1050A alloy, subjected to the heat treatment described in [8] for giving back a conventional yield stress of 25 MPa, an ultimate strength of 80 MPa and a ductility of ε_u=45%, has been used for the aluminum shear panels. Instead, for the steel specimens a more conventional material, namely the steel S235, has been adopted.

Apart from the specimens listed above, also other different solutions of shear panels, tested during previous experimental campaign, have been considered for comparison purposes. As for the aluminum panels, the comparison has been done with the results obtained by tests carried out on two stiffened shear panels. The first, named as BTPASP-type 1, is given by a 500x500 mm and 5 mm thick aluminum shear plate with stiffeners at support only; the latter, named as BTPASP-type 3, instead, presents stiffeners at support and two transversal and two longitudinal stiffeners that reduce the free buckling length of the shear plate. For both the two panels, the heat treated EN-AW-1050A alloy mentioned above has been used. As shown by studies of the past [17], the shear panel BTPASP-type 3 has a fully dissipative behavior, because of the effectiveness of the applied stiffeners. Instead, panel BTPASP-type 1 presents a cyclic response that is significantly influenced by buckling phenomena.

As for the steel specimens, their response has been compared with the ones offered by analogous shear plates without any type of technologies able to avoid the trigger of buckling phenomena. These have been named as StSP8-0.8 mm thick steel shear panel and StSP25-2.5 mm thick steel shear panel, for plates of 0.8 mm and 2.5 mm respectively.

2.3 The loading protocol

All the tested panels have been diagonally loaded through a MTS810 machine, following the cyclic quasi-static protocol provided by ECCS-CECM [18]. 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. Test Results

3.1 Aluminum Specimens

The hysteretic responses of the buckling inhibited aluminum specimens are shown in Fig. 5 in terms of shear stress-shear strain relationship. The obtained large loops testify the high dissipative capacity of the tested panels, also for high shear demands. Significant strength degrading effects have been registered only beyond a diagonal displacement of ±40.00 mm, corresponding to a shear strain demand of about ±9.00%.

The comparison between obtained results evidences that specimen “t-BIP” performs better than the “p-BIP” one, the latter being affected by some secondary buckling phenomena developed during the test. In addition for “t-BIP” specimen a confinement adjustment effect was observed. This is similar to the one related to the “compressive adjustment factor” already evidenced for buckling restrained braces, leading to a general increasing of strength for large deformation.

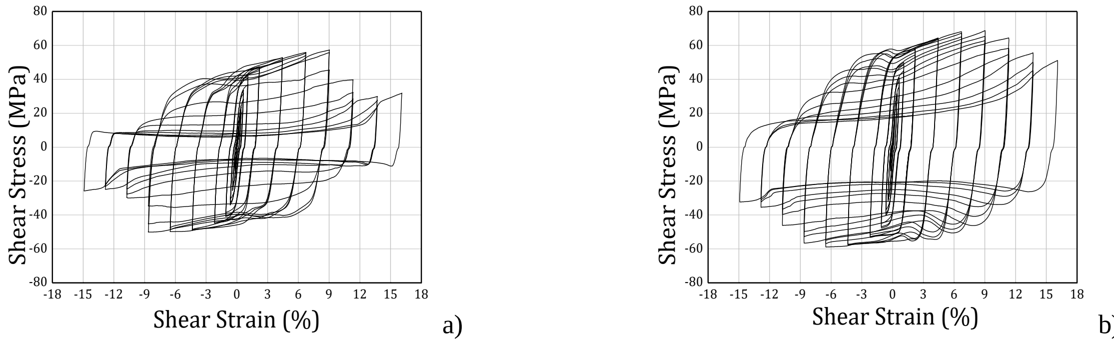


Fig. 5. The obtained hysteretic cycle of the aluminum specimens: a) “p-BIP” and b) “t-BIP”.

As stated before, in order to examine the performance offered by tested specimens, the obtained experimental results have been compared in terms of global parameters with the outcomes retrieved from another experimental campaign carried out on analogous (for geometry and material) pure aluminum shear panels which were conceived according to a more traditional practice. In particular, two previously tested panels. BTPASP-type 1 and BTPAS-type 3, have been considered.

With the aim of comparing the different dissipative capacity of the systems, an “energy efficiency factor” η has been introduced. This parameter represents the ratio between the area of the actual hysteretic cycle get for the generic shear strain, namely the dissipated energy E_d, and the area of an ideal cycle obtained, for the same demand, by reversing an ideal bilinear elasto-plastic curve, which is considered as the potential optimal response of the proposed device (Fig. 6.a). The adopted bilinear relationship has the first elastic branch characterized by a slope k_1 read on the tangent to the unloading branch of the cycle of the real hysteretic response and it is characterized by a post-elastic stiffness k_2 read as the slope of the tangent of the envelope curve of each experimental cycle (Fig 6.b).

According to the values obtained for the elastic stiffness k_1 (about 12000 MPa and 15000 MPa for shear panels with conventional stiffeners and shear panels with buckling restrained plates respectively) and the post-elastic stiffness k_2 (Fig. 7a), the obtained values of the energy efficiency factor η are given in Fig. 7b, with reference to the larger cycle experimentally registered for each shear strain demand.

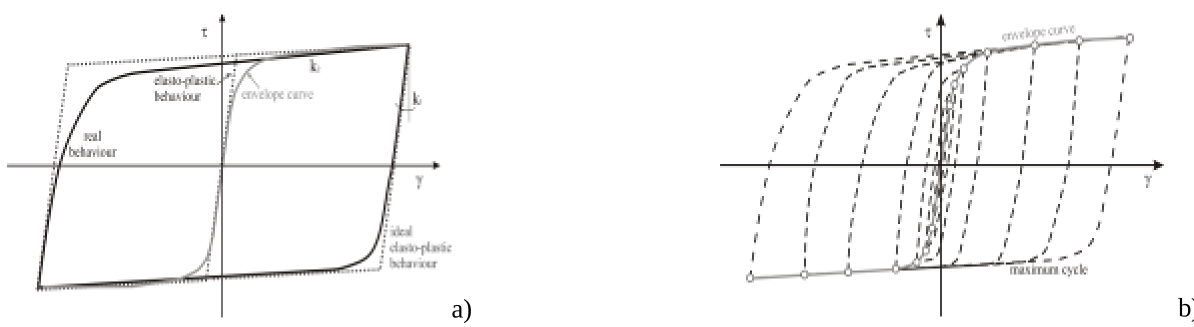
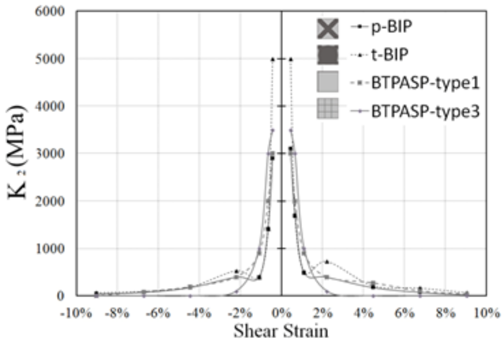


Fig. 6. a) Definition of the energy efficiency factor η and b) determination of the envelope curve of the experimental cycle.

In addition, by the analysis of the equivalent viscous damping factor ξ_{eq} given in Fig. 8a, which retrieves a measure the fractional part of the strain energy (E_s) dissipated during each deformation cycle, it should be recognized, that *i*) both buckling inhibited and multi-stiffened shear panels allow increasing of about 1.3 times the dissipative capacity of the simple plate in shear and *ii*) the specific energy dissipated by “BTPASP type 3”shear panel is larger than the one offered by the buckling inhibited plates for very large shear strain demands, namely greater than 4% and 6.5% for p-BIP and t-BIP, respectively.

With reference to the last comment, it is to be pinpointed that although shear panel “t-BIP” presents always larger hysteretic cycles with respect to other panels, the lower ξ_{eq} factor registered for very large shear deformation is due to the fact that the strain energy is higher as well. This is justifiable because of the higher strength caused by the confinement adjustment effects which has been discussed previously.



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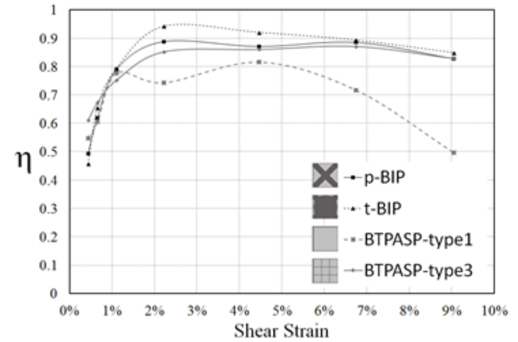
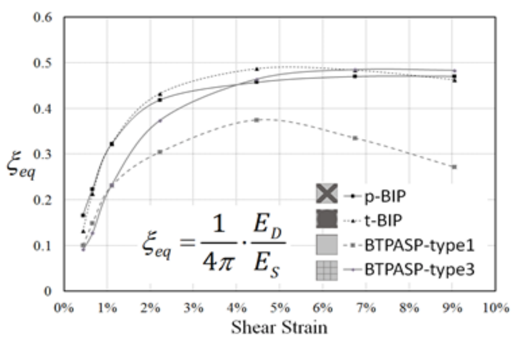


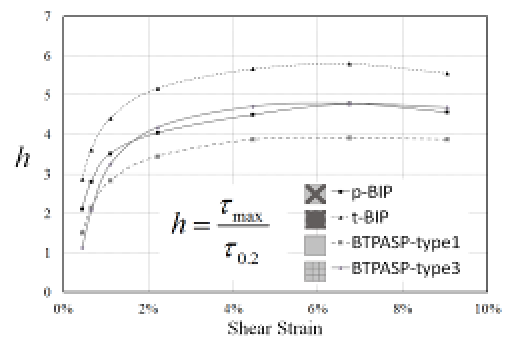
b)

Fig. 7. (a) Post elastic stiffness and (b) energy efficiency factor values for the analyzed aluminum shear panels

For a better comprehension of this phenomenon, in Fig. 8.b the variation of hardening ratio h, defined as the ratio between the maximum attained shear strength for each shear demand and the conventional yielding one, is shown. From the same figure it is also evident that the "t-BIP" solution and the "BTPASP type 3" shear panel provide a similar strength for medium and high shear strain levels, whereas the stiffened plate is clearly weaker for smaller strain levels.



a)



b)

Fig. 8.(a) Post elastic stiffness and (b) energy efficiency factor values for the analyzed aluminum shear panels

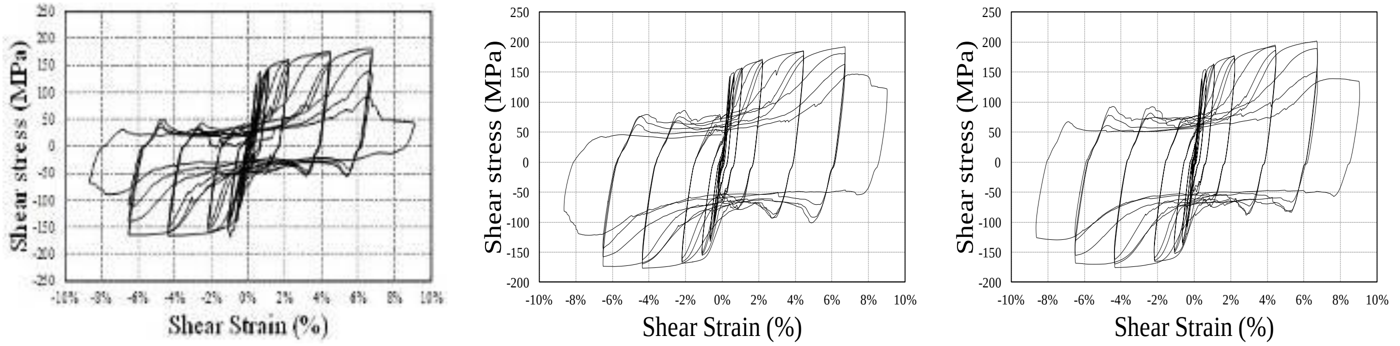
3.2 Steel Specimens with 0.8 mm thickness

Before of commenting the results obtained for both the 0.8 mm and 2.5 mm steel panels, it is important to pointed out two technological aspects that influenced their response.

In fact, the used testing apparatus has been initially designed for a 5 mm thick pure aluminum shear panel which, as referred before, has been considered 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 aluminum 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.

In Fig. 9, the hysteretic response obtained by the test carried out on 0.8 mm thick steel specimens, are reported. In this case, differently by the case of aluminum specimens, also the cycles given by the bare panel are shown, as, for steel panels, the comparison also in terms of hysteretic cycles is of a certain interest.

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 the inhibited 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.



a) b) c)

Fig. 9. Hysteretic cyclic response of a) “StSP 08”, b) “p-BIPSt08”, c) “t-BIPSt08” 0.8 mm thick steel specimens.

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 (Fig. 10a and 10b), this meaning 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 confirming that the inhibition action could have a certain level of effectiveness also in presence of the above technological criticalities. This aspect is also evident by analyzing the panels response in terms of equivalent viscous damping (Figure 10c) which, for the buckling inhibited panels, is almost of 30% when shear strains higher than 4% are attained, whereas the same parameter is of 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. 10d) and hardening ratio (Fig. 10e), 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 center of the plate.

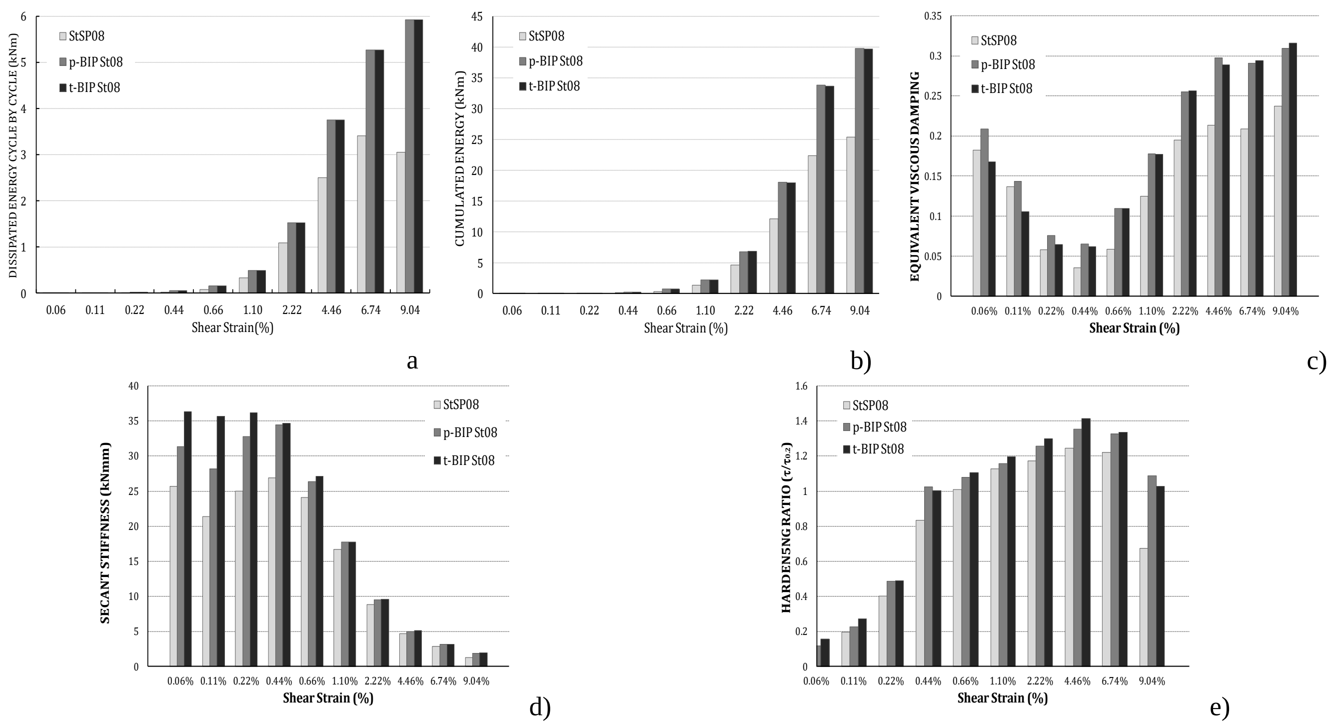
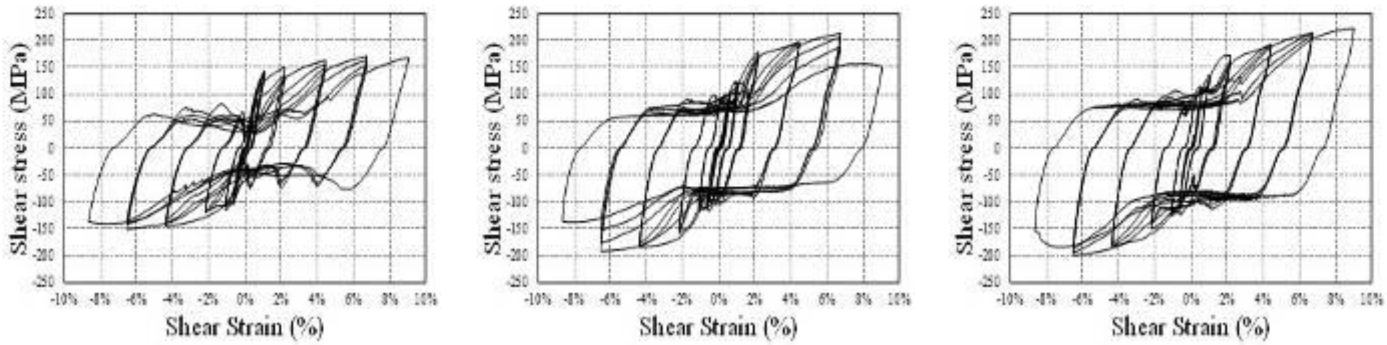


Fig. 10. Comparison between “StSP08”, “p-BIPSt08” e “t-BIPSt08” in terms of: a) dissipated energy by cycle, a) cumulated dissipated energy, e) equivalent viscous damping, d) secant stiffness, e) hardening ratio

3.3 Steel Specimens with 2.5 mm thickness

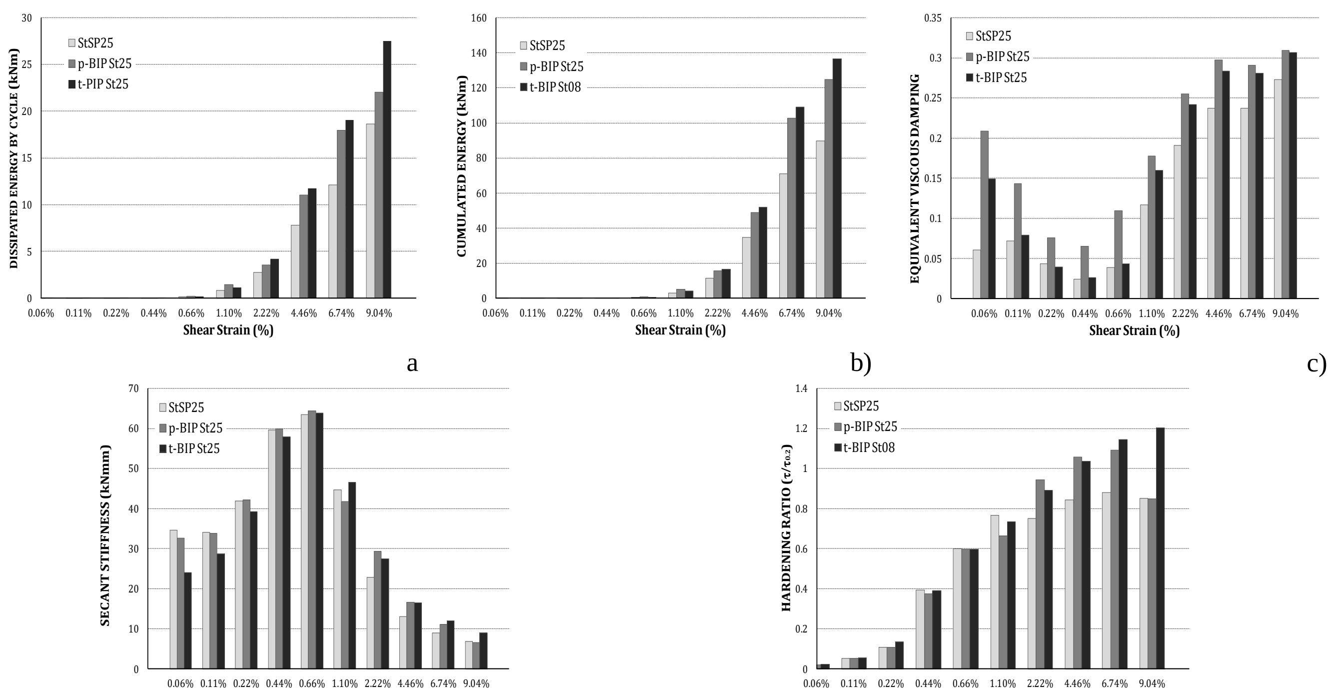
In Fig. 11 the hysteretic cycles of the tested 2,5mm tick specimens are illustrated. Also in this case, some buckling phenomena have been noticed even for the buckling inhibited panels. Nevertheless, the reduced gap between the restraining and the restrained plates has entailed that the detrimental effects 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.



a) b) c)

Figure 11. Hysteretic cyclic response of the 2.5 mm thick plates: a) "StSP 25", b) "p-BIPSt25", c) "t-BIPSt25".

The above remarks are also confirmed by the analysis of the global behavior parameters shown in figure 12. The energy per cycle dissipated by the "t-BIPSt25" specimen is 1.3 times the one of panel "t-BIPSt25". Moreover, in this case, the decay of strength observed for the totally buckling inhibited panel, when very high shear strain demands are attained, is not be observed.



a b) c)

d) e)

Fig. 10. 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

3.4 Experimental evidences

In the following Tabs. 1, 2 and 3, the experimental evidences observed during the tests are synthetically reported and commented. A more in-depth description of those is provided in [15] and [19].

Table 1. Experimental evidences for the aluminium buckling inhibited shear panels.

Shear strain range (diagonal displacement)	**p-BIP**	**t-BIP**
[0, ±0.11%] ([0, ±0.50 mm])	Elastic behaviour	
[±0.11%, ±0.66%] ([±0.50 mm, ±3.00 mm])	Inelastic behaviour without buckling phenomena	
[±0.66%, ±4.40%] ([±3.00 mm, ±20.00 mm])	Buckling of the plate portions not covered by the external device. Small influence on the hysteretic response	Inelastic behaviour without buckling phenomena
[±4.40%, ±6.74%] ([±10.00 mm, ±20.00 mm])	Development of considerable instability waves of plate portions not covered by the external device. Small influence on the hysteretic response	Local buckling phenomena of the plate portions close to the frame arms, not covered by the external plates. Slight pinching effects on the dissipative cycle
[±6.74%, ±9.04%] ([±20.00 mm, ±40.00 mm])	Cracks on the base plate vertexes	
[±9.04%, ±11.37%] ([±40.00 mm, ±50.00 mm])	Collapse of the system	

Table 2. Experimental evidences for the 0.8 mm steel buckling inhibited shear panels.

Shear strain range (diagonal displacement)	**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])	Inelastic behaviour without buckling phenomena	
[±0.66%, ±2.20%] ([±3.00 mm, ±10.00 mm])	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 inhibition system	Panel Damage at the vertexes of the plate
[±4.40%, ±9.04%] ([±20.00 mm, ±40.00 mm])	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
[±9.04%, ±11.37%] ([±40.00 mm, ±50.00 mm])	Collapse of the system	

4. Conclusion

The presented experimental tests confirmed that buckling inhibited shear panels could 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 systems made of pure aluminum thicker plates allows to outline some conclusive remarks about the counter-indications that can arise when the system is not well conceived, when 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.

Table 3. Experimental evidences for the 2.5 mm steel buckling inhibited shear panels.

Shear strain range (diagonal displacement)	**p-BIP St 08**	**t-BIP St 08**
[0, ±1.10%] ([0, ±5.00 mm])	Elastic behaviour	
[±1.10%, ±2.20%] ([±5.00 mm, ±10.00 mm])	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])	Panel damage closed to the connection system	
[±4.40%, ±6.74%] ([±20.00 mm, ±30.00 mm])	Panel damage close to the restraining plate	Panel damage closed to the restraining plate
[±6.74%, ±9.04%] ([±30.00 mm, ±40.00 mm])	Collapse of the system	

In particular:

- when buckling inhibited shear panels are designed, it is necessary to manage in a careful way the gap, which could be particularly large 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.

4. Acknowledgements

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