16th World Conference on Earthquake, 16WCEE 2017

Santiago Chile, January 9th to 13th 2017

Paper N° 933

Registration Code: S-O1461948162

EXPERIMENTAL TESTS ON DISSIPATIVE CLADDING CONNECTION SYSTEMS OF PRECAST STRUCTURES

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Abstract

This paper presents the main results of an experimental campaign carried out within the FP7-SME European research project SAFECLADDING devoted to the improvement of the seismic performance of precast structures with cladding panels. The beneficial effects of dissipative cladding connection systems in providing additional structural damping through energy dissipation mechanisms, mainly based on plasticity and friction, are investigated. Different types of connectors are considered, including a panel-to-column and two panel-to-panel connection devices. The panel to-column device is designed for horizontal panels and consists of a steel plate folded at right-angle along three lines to get a W-shaped profile. In this way, the dissipative connection system allows to achieve stiffness and strength against out-of-plane loading, as well as flexibility and ductility to accommodate in-plane panel-to-structure relative displacements. The panel-to-panel connectors are friction-based or plasticity-based devices made by steel plates inserted into appropriate recesses within the joints in between vertical or horizontal panels. If the panels are connected to the frame structure by means of statically determined schemes, the panel-to-panel dissipative connections make the whole façade much stiffer and integral part of the earthquake resisting system up to the force associated with the friction threshold or yielding of the devices. Cyclic experimental tests on both single dissipative connectors and structural sub-assemblies consisting of two full scale panels have been performed at the Laboratorio Prove Materiali of Politecnico di Milano to investigate the hysteretic behavior of the devices considering different technological features, restraint conditions, and loading protocols. Cyclic and pseudo-dynamic experimental tests have also been performed at the European Laboratory for Structural Assessment of the Joint Research Centre of the European Commission on full scale prototypes of precast buildings with vertical or horizontal panels. The results of the experimental tests confirm the remarkable improvement of the seismic performance of precast structures based on the beneficial effects of dissipative cladding connections, which can provide suitable energy dissipation capacity and limit forces and displacements under earthquake excitation.

Keywords: Seismic design; Precast structures; Cladding panels; Dissipative connectors; Experimental tests.

1. Introduction

The inadequate seismic behavior of the cladding panel connections of precast structures and the consequent structural failures occurred under recent seismic events in Southern Europe, including the 2009 L'Aquila earthquake and 2012 Emilia earthquake in Italy, indicate that a revision of both technology and design criteria of this type of systems is necessary [1, 2]. To solve this problem, a general framework for the seismic design of precast structures based on innovative fastening systems of the cladding panels has been proposed and investigated within the SAFECLADDING research project supported by a grant of the European Commission as part of the program FP7-SME-2012 [3]. This research activity included solutions for existing and new precast structures with isostatic, integrated, and dissipative connection systems of the cladding panels [4-9].

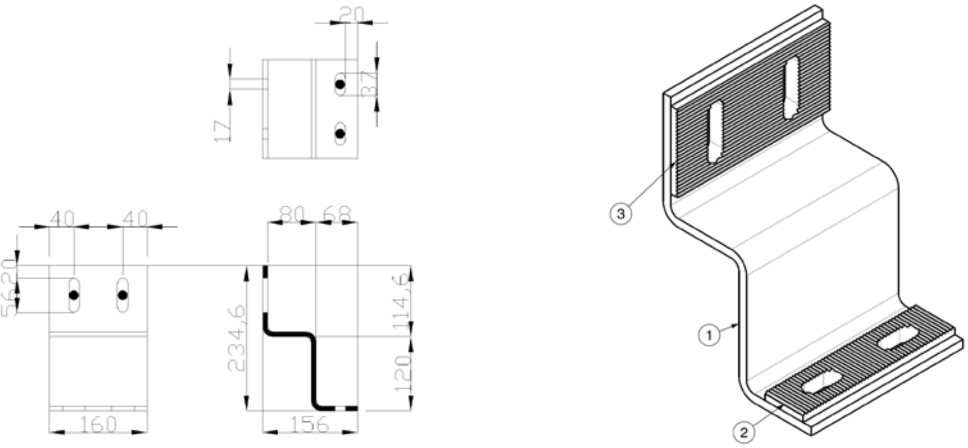
The beneficial effects of dissipative cladding connection systems in providing additional structural damping through energy dissipation, mainly based on plasticity and/or friction, have been shown in [10-14] based on experimental tests and numerical investigations. This paper presents the main results of an experimental campaign carried out on different types of dissipative connections, including a panel-to-column connector for horizontal panels and two panel-to-panel connection devices for both vertical and horizontal panels.

The panel to-column Folded Plate Device (FPD) consists of a steel plate folded at right-angle along three lines to get a W-shaped profile, as shown in Fig. 1 for the tested connector [13, 14]. The longer internal plate segment is parallel to the column side, and the shorter is parallel to the panel surface. The end segments are equipped with thick toothed plates welded along the edges, with passing horizontal slots at the column side and passing vertical slots at the panel side. The slots ensure horizontal and vertical tolerances and their length should be designed in order to allow the post-installation of the fastener with clearance of the reinforcing bars cast in both the column and the panel. The connection is completed by the application of post-installed fasteners, for use in existing structures, or bolting in pre-installed sockets, both provided with closing nuts and counter-toothed washers. This dissipative connection system allows to achieve stiffness and strength against out-of-plane loading, as well as flexibility and ductility to accommodate in-plane panel-to-structure relative displacements.

The panel-to-panel connectors are plasticity-based or friction-based devices made by steel plates inserted into appropriate recesses within the joints in between vertical or horizontal panels. If the panels are connected to the frame structure by means of statically determined schemes, the panel-to-panel dissipative connections make the whole façade much stiffer and integral part of the earthquake resisting system up to the force associated with the yielding or friction threshold of the devices [10, 12, 13].

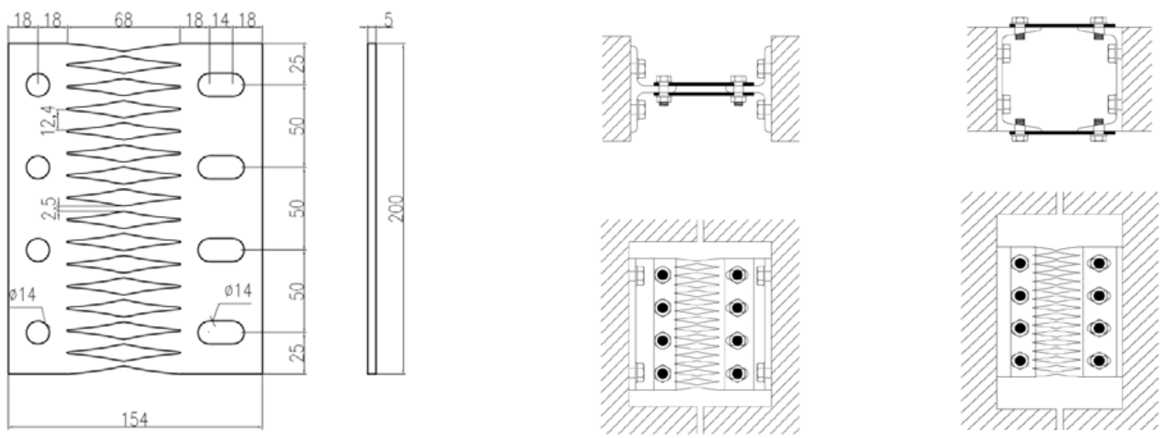
The plasticity-based Multiple Slit Device (MSD) consists of steel plates with slits of various shapes and sizes which realize a set of elementary beams. MSDs with different configurations of the elementary beams are presented in [7, 13]. Fig. 2 shows the tested MSD with elementary beams having hourglass profile with uniform yielding bending moment. The cusp at the theoretical zero-depth at mid-span is smoothed to a minimum depth equal to 20% of the depth at beam ends. The slits allow to modify the shear-type behavior of the rectangular plate to the flexural-type behavior of the elementary beams, which allows for larger energy dissipation capacities. The steel plates are assembled through bolts on T-shaped, UPN or angle profiles. The web of the T-shaped profile is provided with holes for the bolted connection with two plates. UPN flanges are provided with threaded holes for the direct application of the bolts from the external side.

The Friction Based Device (FBD) is made by the assemblage of brass sheets, cover steel plates, and support steel profiles, as shown in Fig. 3 [7, 10 - 13]. The brass sheets are provided with two round holes near one edge and two horizontal slots near the other edge to allow for the bolted connection with the support profiles and provide a mounting tolerance related to the length of the slots. The cover steel plates have the same geometry of the brass sheets and prevent the brass sheets to deform. The support steel profiles can be symmetric (T-shaped) or asymmetric (angles). The profiles are provided with holes on the panel side and with vertical slots that allow the mutual vertical displacement between the two adjacent support profiles. Symmetric profiles lead to a distribution of forces that allows to avoid torsional effects. However, in such case the assemblage needs to be performed from two sides in order to tighten all bolts. Asymmetric profiles involve torsional actions in the panel connection, but allow the assemblage to be performed from one side only, usually the inner side of the building.



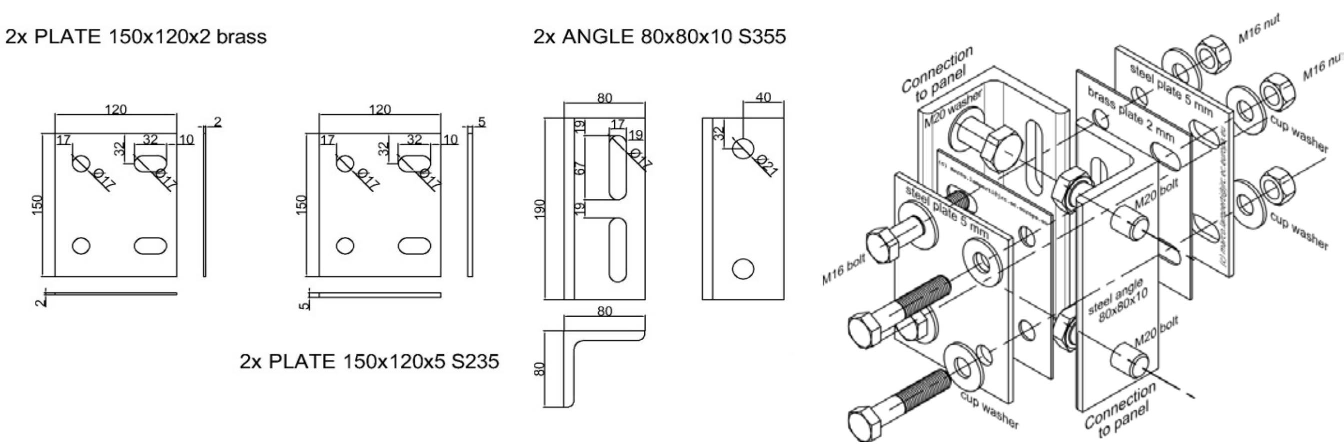
(a) (b)

Fig. 1 – Folded Plate Device (FPD): (a) geometrical dimensions and (b) 3D view of the connector.



(a) (b) (c)

Fig. 2 – Multiple Slit Device (MSD): (a) multiple slit plate and assemblage on (b) T-shaped and (c) UPN profiles.



(a) (b)

Fig. 3 - Friction Based Device (FBD) with angle supports: (a) geometrical dimensions of the components and (b) 3D view of the assemblage (courtesy of Marco Lamperti).

Fig. 4 shows a view of the three connectors installed on precast structures. Their hysteretic behavior and seismic performance have been investigated within the SAFECLADDING project based on experimental tests on single connectors, structural sub-assemblies, and full scale prototypes of precast buildings with dissipative connections of the cladding panels. The main results of this experimental campaign are presented and discussed.

(a) (b) (c)

Fig. 4 – View of the dissipative panel connections: (a) FPD; (b) MSD; (c) FBD.

2. Experimental program

Cyclic experimental tests on both single dissipative connectors and structural sub-assemblies consisting of two full scale panels have been performed at the Laboratorio Prove Materiali (LPM) of Politecnico di Milano considering different technological features, restraint conditions, and loading protocols.

The tests on single devices have been carried out on a uni-axial ± 1000 kN Schenck test machine under imposed displacement histories. The connections are tightened through bolts to a strong support made by two L-shaped HEA steel profiles welded together. The L-shaped profiles are then tightened to the machine through nailed thick steel plates provided with large diameter bolts. Fig. 5.a shows a picture of the test setup with a device under testing.

The panel sub-assembly test setup, shown in Fig. 5.b, is made of two single layer concrete panels 129×323×16cm, with an aspect ratio of 2.5. The panels are provided with an upper passing vertical slot in the middle of the panel width, leading to a vertical distance from the bottom panel-to-foundation connection to the top panel-to-beam connection of about 260 cm. Three recesses are placed at 1/4, 2/4 and 3/4 of the vertical distance at each side of the panels to connect the dissipative devices. The top panel connection is made with round holes hosting steel pins that link the panels to the steel articulated frame through which the imposed displacements are applied to the panels. The frame is made with two HEA columns hinged both at the bottom with a strong steel beam and at the top with two parallel UPN beams placed at the sides of the panels. The hinges are made by steel pins and forks. The frame is connected to a horizontal 750 kN jack fixed to the strong steel braced reaction frame of the lab at a height of 270 cm, in axis with the beam-to-column pins. A lateral displacement retainer system has been installed in correspondence of the steel beam and attached to it with steel spheres that are fixed to lateral stiff retaining frames. Two vertical long slots are cut in the UPN profiles in order to locate the panel-to-beam connection pins. The panel-to-foundation connection is also hinged with pin and forks.

Cyclic and pseudo-dynamic experimental tests have been also performed at the European Laboratory for Structural Assessment (ELSA) of the Joint Research Centre (JRC) of the European Commission on full scale prototypes of a precast structures with vertical or horizontal panels. The structural prototype has been tested with different configurations of horizontal and vertical cladding panels and different connections systems, including isostatic, integrated, and dissipative systems, under cyclic and pseudo-dynamic load protocols performed at different levels of seismic action. A complete description of the structural prototype, test setup, and testing program, can be found in [15]. The large number of tests performed included structural configurations with vertical panels equipped with FBDs and structural configurations with horizontal panels equipped with post-installed FPDs. Fig. 5.c shows a view of the structural prototype with vertical cladding panels. This structure consists of two longitudinal two-bay frames and a single span slab roof and is provided with 6+6 solid vertical panels 2.49x8.40 m with thickness of 0.20 m. The panels have a recess at the base to accommodate a hinged connection and three recesses along the lateral sides to accommodate the FBDs. The connection system of the panels includes a steel shear connector at the top and a steel cylindrical hinge at the bottom placed along the vertical mid-axis of each panel. The bottom hinge prevents the rotation around the vertical axis, and two push-pull connections have been left acting at the top of panels as additional safety rods. Two repartition steel beams distribute over the roof slab the horizontal force transferred by the actuators.

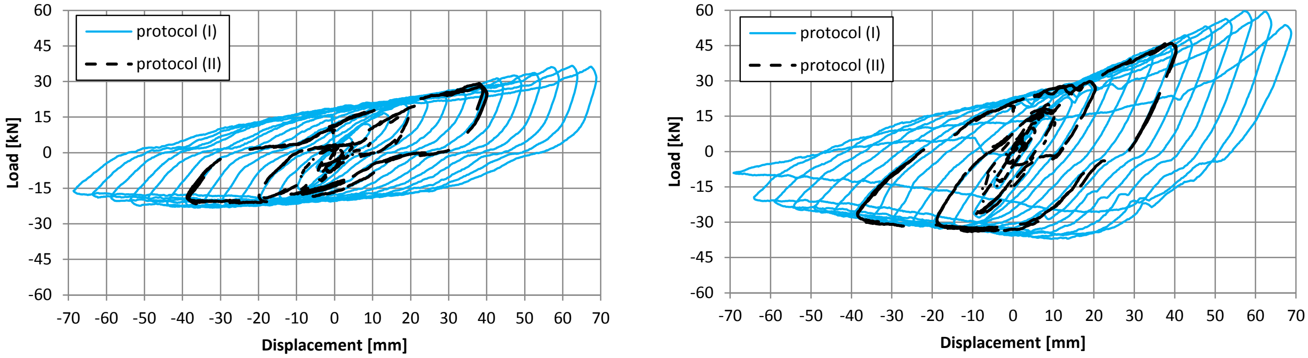
(a) (b) (c)

Fig. 5 - Test set-up: (a) local tests on single connectors; (b) sub-assembly tests; (c) full-scale prototype tests.

3. Folded Plate Device

Local tests have been carried out on FPDs considering the effect of the panel out-of-plane restraint by allowing or preventing the horizontal displacement of the test machine. Two cyclic protocols have been used. The displacement history of protocol (I) applies single cycles with amplitude steps of 5 mm up to failure. The displacement history of protocol (II) applies triple cycles with doubled amplitude steps up to 40 mm. The results are reported in Fig. 6. A stable hysteresis is observed through all tests. The results of the tests with different protocols overlap with precision, highlighting the stable mechanical behavior of the device. No relevant stiffness or strength degradation has been observed through the cycles. Good energy dissipation properties are achieved, associated to the plasticization of steel.

The hysteretic behavior is strongly influenced by the out-of-plane restraint. In particular, the behavior is fairly symmetric for free displacement condition with an elastic-plastic backbone curve showing a slight hardening in the phase of extension of the device and a plateau in the phase of contraction of the device (Fig. 6.a). The behavior turns into strongly asymmetric if the panel out-of-plane displacement is restrained, with an elastic-plastic backbone curve showing a strong hardening in the phase of extension of the device and a relevant softening in the phase of contraction of the device (Fig. 6.b). Fig. 7 shows deformed configurations with large plastic deformation of the device with unrestrained (Fig. 7.a) and restrained (Fig.7.b) out-of-plane displacement.



(a) (b)

Fig. 6 – Local tests on FPDs: load vs displacement cycles for (a) unrestrained and (b) restrained out-of-plane displacement.

(a) (b)

Fig. 7 - Local tests on FPDs: deformed configurations with large plastic deformation for (a) unrestrained and (b) restrained out-of-plane displacement.

Both cyclic and pseudo-dynamic tests have been carried on the full-scale prototype with horizontal panels. Two FPDs per panel have been post-installed with fasteners on panels seating on strong panel-to-column steel brackets allowing panel in-plane sliding and connected at the top with shear keys to the columns. The comparison of the cyclic behavior of the structure with FPDs vs the bare frame structure displaced up to about 1% of drift is shown in Fig. 8. These results indicate that the introduction of FPDs brings to an almost doubled stiffness of the structure, to which also corresponds a moderate added energy dissipation capacity.

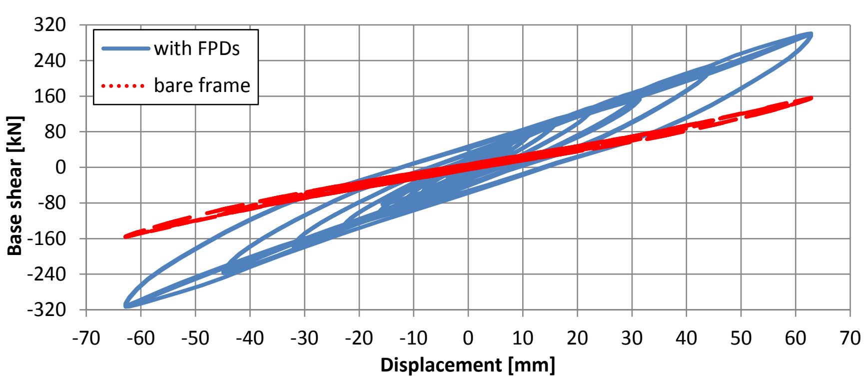
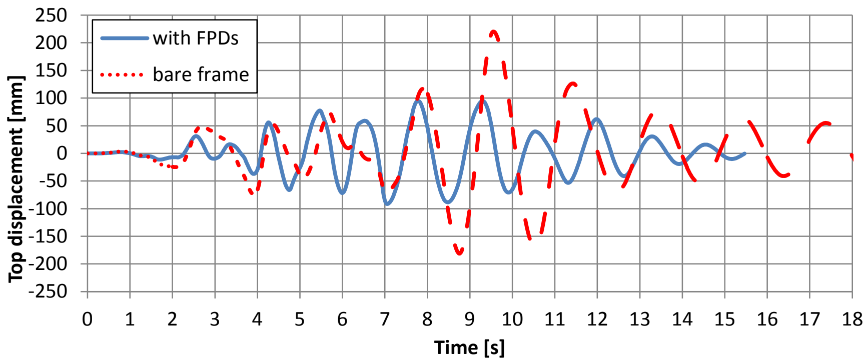
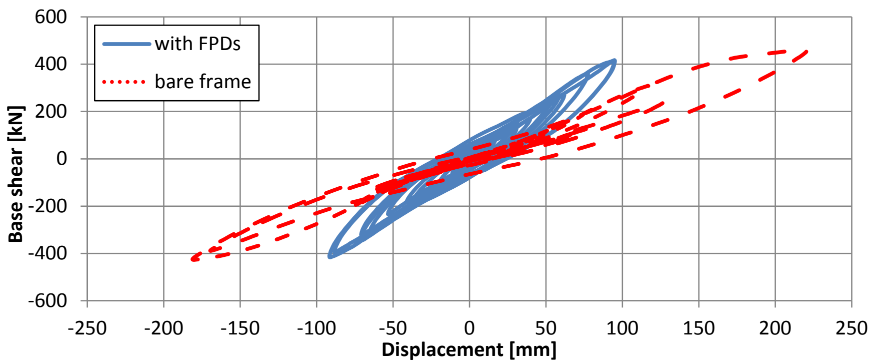


Fig. 8 – Full-scale cyclic tests: comparison of the base shear vs top displacement for the structural prototype with FPDs and the bare frame.

The results of a pseudo-dynamic test carried out with a modified Tolmezzo accelerogram scaled at the peak ground acceleration PGA=0.36g are reported in Fig. 9 for both the structure with FPDs and the bare frame structure. It can be observed how the FPDs bring to a reduced maximum displacement, and consequently to lower damage, due to the combined effects of added stiffness and dissipation of energy.



(a)



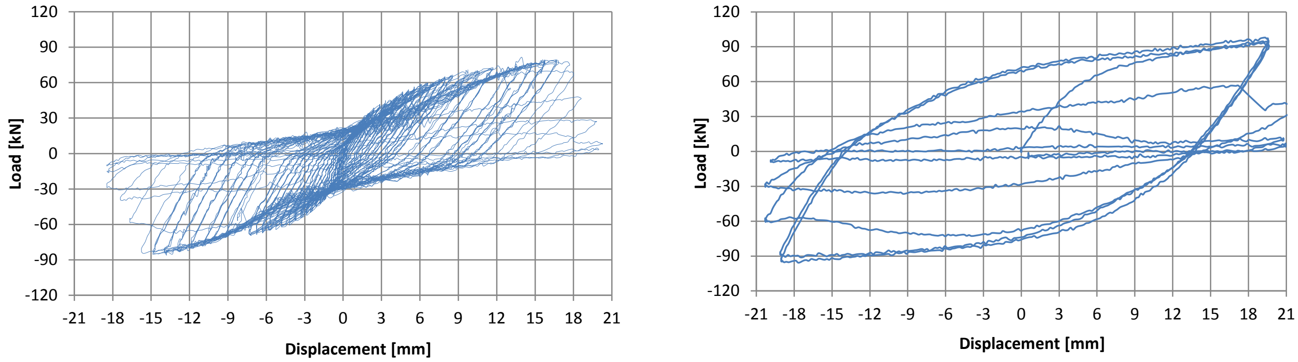
(b)

Fig. 9 - Full-scale pseudo-dynamic tests (PGA = 0.36g): structural prototype with FPDs vs the bare frame in terms of (a) top displacement time history and (b) base shear vs top displacement.

4. Multiple Slit Device

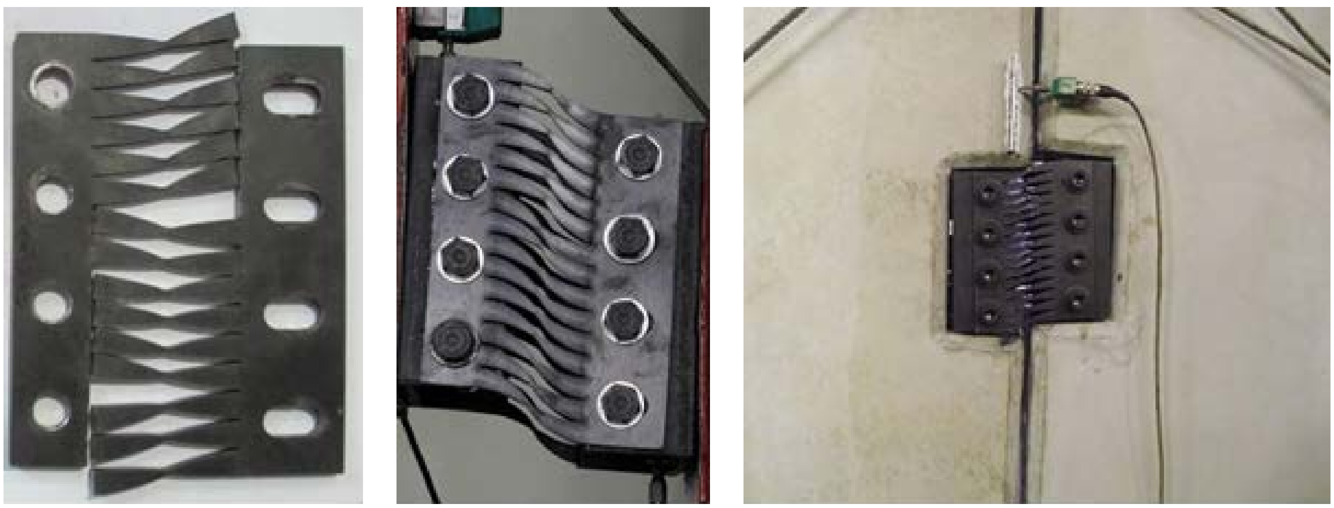
Local tests have been carried out on MSDs to characterize their mechanical behavior and their stability under cyclic loading at both small and large displacement values. The results, shown in Fig. 10, highlight an elastic-plastic behavior of the device with a relevant hardening. Dissipation of energy occurs through plasticization of the ductile elementary beams of the two steel plates. The results shown in Fig. 10.a are achieved with triple cycles and amplitude increment of 0.5 mm up to 10 mm, followed by amplitude increments of 1 mm. The hysteresis is stable for displacements up to about 20% of drift of the device. After this threshold, the hysteresis turns into unstable, bringing to failure of the device by rupture at the ends of the elementary beams, as illustrated in Fig. 11.a. The results shown in Fig. 10.b refer to a cyclic protocol with ten cycles with amplitude of 20 mm, corresponding to about 30% of drift of the device. The connection is able to attain this large displacement, as shown in Fig. 11.b, but fails after few cycles for oligo-cyclic fatigue.

Two panel sub-assembly cyclic tests have been performed with a single MSD installed between the two concrete panels. The results, shown in Fig. 12 in terms of load vs vertical relative displacement (Fig. 12.a) and load vs top displacement (Fig. 12.b), reproduce the local behavior of the connection characterized through local tests. Fig. 11.c shows a deformed configuration at large deformation. The global behavior of the assembly is, however, characterized by a reduced stiffness owing to the deformability of the different components of the sub-assembly, including the panel-to-structure pinned connections.



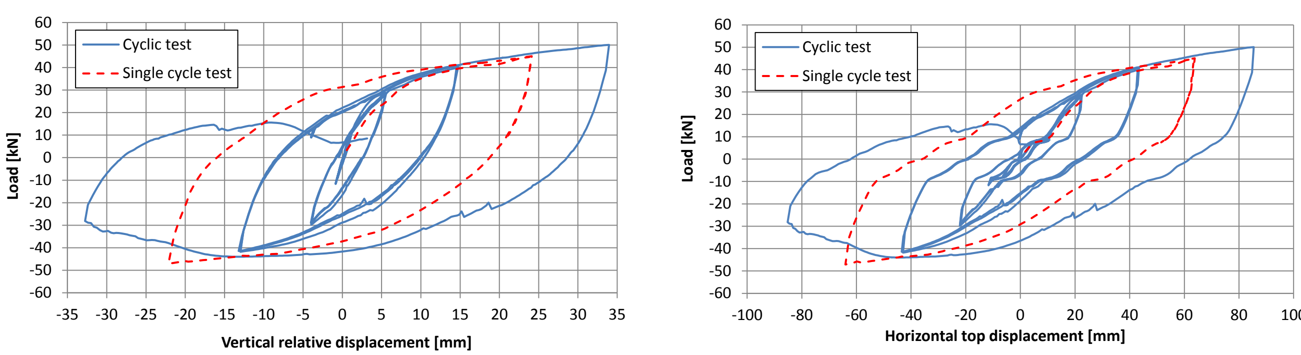
(a) (b)

Fig. 10 - Local tests on MSDs: load vs displacement diagrams for (a) low-displacement and (b) large-displacement cyclic protocols.



(a) (b) (c)

Fig. 11 – MSDs: (a) failure mode, and deformed configurations during (b) local test and (c) sub-assembly test.



(a) (b)

Fig. 12 - Sub-assembly tests on MSDs: (a) load vs vertical relative displacement, (b) load vs top displacement.

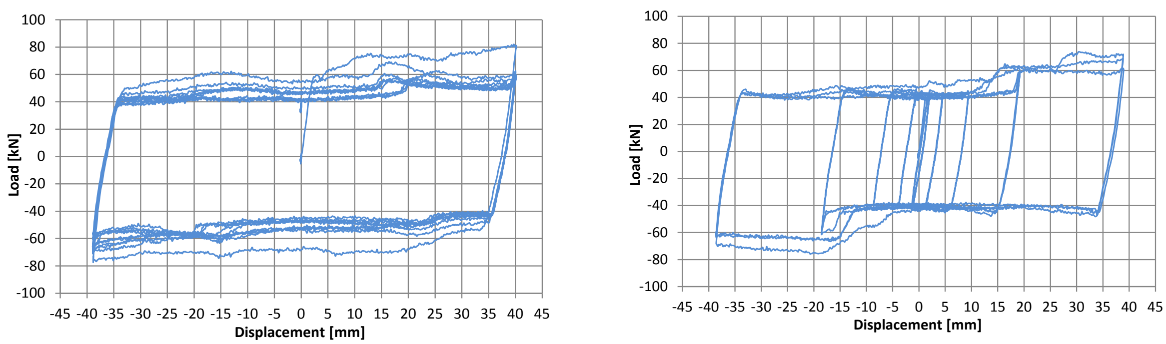
5. Friction Based Device

Local tests have been carried out on FBDs to characterize their mechanical behavior under cyclic loading. Two loading protocols have been applied, with ten times constant displacement amplitude cycles at ± 40 mm, and three cycles with displacement amplitude doubling at each step up to ± 40 mm, respectively.

Several tests have been carried out to investigate the influence of different technological features on the hysteresis and dissipation capacity of the device. The results of this experimental campaign allowed several improvements of the initial design, including the use of brass sheets to stabilize the cycles and avoid locking of the connection, with consequent failure, the use of Belleville washers to be coupled with the bolts for tightening of the connection, and the safe re-use of the components of the connection after seismic events.

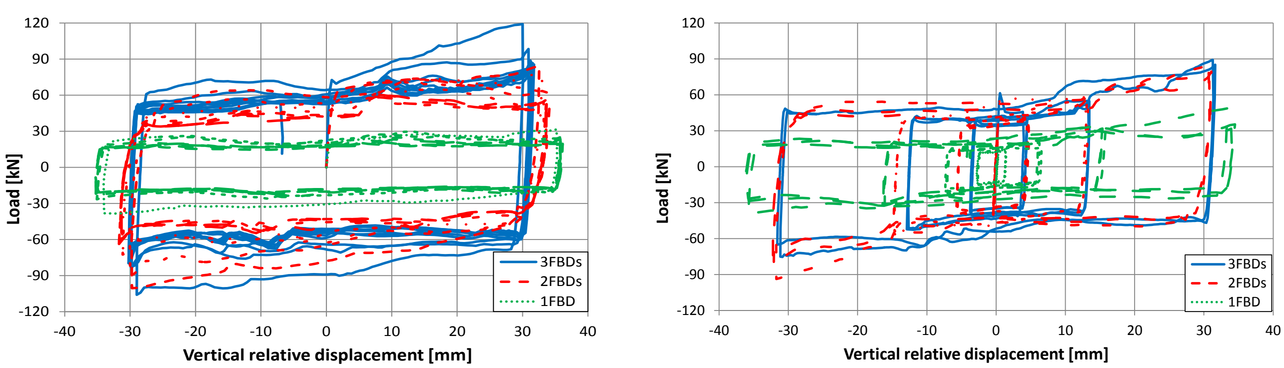
The results of the tests performed on the improved device, tightened to attain a shear threshold load of 60 kN, are reported in Fig. 13 for both loading protocols. It can be observed that the hysteretic cycles enclose a large area, to which corresponds a large dissipation of energy through brass-steel friction. The hysteresis is very stable and characterized by a large initial stiffness and a well-defined plateau. The slip load threshold is however affected by moderate uncertainty, due to both unavoidable randomness of the friction mechanism and bolt losses through cycles, only partially reduced by the use of Belleville washers.

Sub-assembly tests have been performed with one, two, and three devices installed at the interface between the two panels. The results for the two loading protocols are compared in Fig. 14. The results indicate that the use of multiple devices at the same panel interface does not lead to a corresponding linear increase of the global slip threshold load, mainly due to the moderate randomness of the response of each single device. This may be observed in Fig. 14, where the cycles corresponding to the use of two and three FBDs tend to overlap.



(a) (b)

Fig. 13 - Local tests on FBDs: load vs displacement diagrams for (a) constant displacement amplitude protocol and (b) increasing displacement amplitude protocol.



(a) (b)

Fig. 14 - Sub-assembly tests on FBDs: load vs displacement diagrams for (a) constant displacement amplitude protocol and (b) increasing displacement amplitude protocol.

Cyclic and pseudo-dynamic tests have been performed on the full-scale prototype building with both vertical and horizontal panels under different connection arrangements. In the following, the main results of the tests on the building with vertical panels are reported. The panels have a pendulum connection arrangement, made with centered hinges at both top and bottom sides. Fig. 15 shows the results with one, two, and three FBDs installed at the interface between adjacent panels. The load protocol applies three cycles with displacement amplitude increased by 40% at each step. The results indicate that the installation of a large number of connections may mitigate the uncertainty related to the single device and lead to a mean slip threshold load that is actually depending on the number of connections per side.

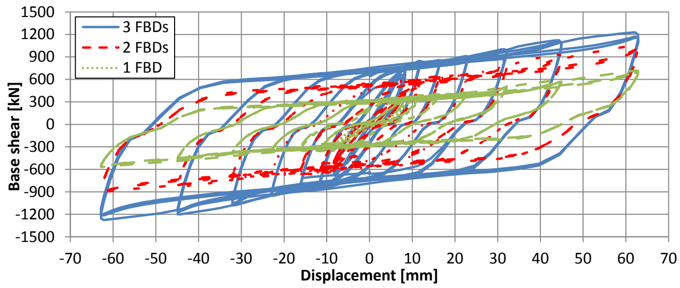


Fig. 15 - Full scale prototype cyclic tests on the structure with FBDs.

The results of the pseudo-dynamic tests under a modified Tolmezzo accelerogram are reported in Fig. 16 for the structural prototype with three FBDs per interface and for different levels of PGA. For PGA=0.18g the response of the structure is very stiff, with displacements limited to about 11 mm, and the dissipative action of the devices is not even activated (Fig. 16.a). For PGA=0.36g the action of the devices is activated and allows to significantly limit displacements, and consequently damage, based on the added stiffness and dissipation of energy (Fig. 16.b). Even for PGA=0.72g and PGA=1.00g, corresponding to, respectively, two and almost three times the no-collapse design capacity of the frame, the structure exhibits a maximum displacement lower than the yielding displacement of the frame (Figs. 16.c and 16.d).

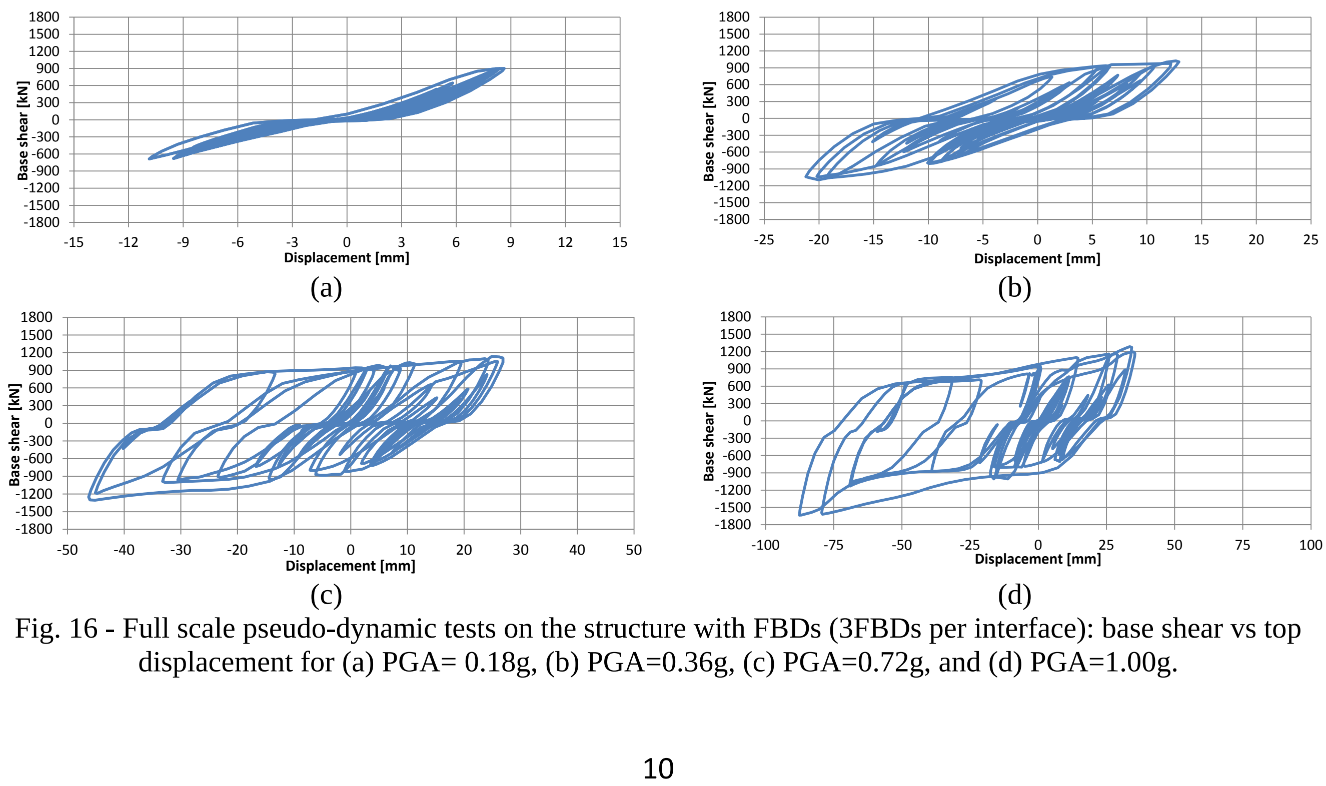
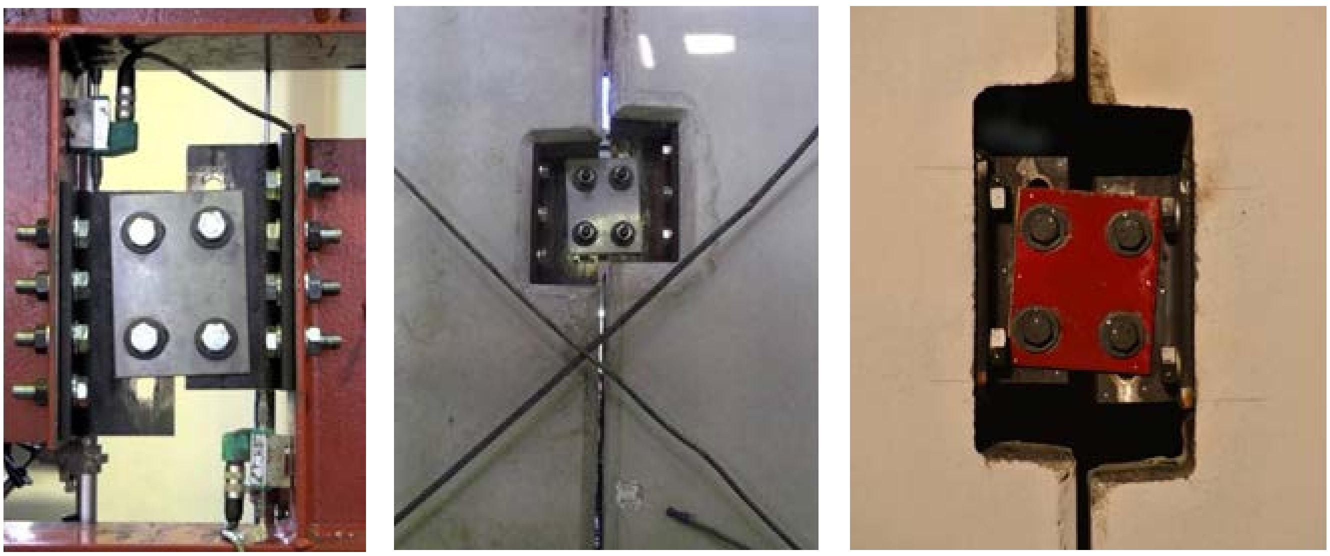


Fig. 16 - Full scale pseudo-dynamic tests on the structure with FBDs (3FBDs per interface): base shear vs top displacement for (a) PGA= 0.18g, (b) PGA=0.36g, (c) PGA=0.72g, and (d) PGA=1.00g.

After the tests the structure and its components, including the FBDs and all other connections, were found completely undamaged. A check of the tightening torque of the FBD bolts highlighted that also axial losses in the bolts were not larger than about 10% after each test.

Fig. 17 shows some views of the FBD during local, sub-assembly, and full-scale prototype testing.



(a) (b) (c)

Fig. 17 – FBDs: configurations during (a) local tests, (b) sub-assembly tests, and (c) full-scale prototype tests.

6. Conclusions

The main results of an experimental campaign carried out on different types of dissipative panel connection devices, namely FPDs, MSDs, and FBDs, have been presented. These results allowed to characterize the mechanical behavior of single devices, to define the correct functioning of their connection with the panels, and to prove their efficiency in improving the seismic performance of precast structures.

FPDs are characterized by a flexible in-plane structural behavior that, in combination with a stiffening effect of the horizontal panel against out-of-plane actions, can provide a stable dissipation of energy through plasticity. The hysteretic stability of the device is satisfactory even at large drift. The response of a single device is strongly influenced by the out-of-plane restraint condition. However, it is worth noting that the symmetric disposition of two devices on a cladding panel allows for a symmetric cyclic response with a smooth and well-defined elastic-plastic backbone curve.

MSDs exhibit a relevant elastic stiffness and a plastic behavior characterized by a pronounced hardening. A stable dissipation of energy is attained through plasticity up to a drift ratio of about 20% with respect to the length of the slits. The device may be able to displace much further, even though entering in a cyclically unstable branch. The displacement capacity of the devices, mainly depending on the length of the slits, is quite limited.

FBDs are characterized by a pseudo-plastic behavior with a high initial stiffness and a plateau associated to the friction load threshold, after which relative sliding of the supports occurs. This friction mechanism leads to large dissipation of energy. The hysteresis of the device is very stable up to the ultimate displacement, which corresponds to the full length of the vertical slots cut in the support profiles. A moderate uncertainty in the slip load threshold is observed, as typical of friction. The device under cycling load is not subjected to damage. Therefore, replacement of the device after a seismic event is not needed.

The results of local tests have been also validated by means of sub-assembly and full-scale prototype tests. It is worth noting that the connections with the concrete panels did not show any damage after these tests.

In particular, the results of full-scale prototype cyclic and pseudo-dynamic tests allowed to confirm that the seismic performance of precast structures with cladding panels can significantly be improved based on the beneficial effects of dissipative panel connections, which can provide suitable energy dissipation capacity and limit forces and displacements under earthquake excitation.

7. Acknowledgements

The work presented in this paper has been funded mainly by the European Commission within the FP7-SME-2011 SAFECLADDING research project (Grant agreement No. 314122, 2012), and partially by the Italian Department of Civil Protection (DPC) and the Italian Laboratories University Network of Earthquake Engineering (ReLUIS) within the research program DPC-ReLUIS 2014-2016. The financial supports of the funding institutions are gratefully acknowledged. Gratitude and appreciation are expressed to Marco Lamperti, Giovanni Lobina, Antonio Cocco, Paolo Broglia, Silvia Bianchi, Giulia Marelli, Giulia Mariani Orlandi, Alessandro Rocci, and Nicola Zoeddu for their contributions to the execution of the tests performed at Politecnico di Milano. The experimental tests on the full scale prototype have been performed at the European Laboratory of Structural Assessment of the Joint Research Centre of the European Commission. Special thanks are due to all members of the JRC team, particularly to Paolo Negro, Marco Lamperti, Javier Molina, and Pierre Pegon.

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