DISSIPATION PANELS FOR SEISMIC RETROFITTING OF BUILDINGS

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Abstract

Introduction of energy dissipation systems has the effect of reducing the seismic energy transmitted to the structural elements, thereby limiting the deformations imposed on the constructions.

A solution named Dissipation Panels, that was conceived for the seismic protection and retrofitting of buildings, is under development. Dissipation Panels correspond to a passive seismic protection system that when incorporated into a structure increases its energy dissipation capacity. Damages in structural members are thus reduced. Dynamic performance of the Dissipation Panels relies on the good cyclic behavior of an embodied replaceable hysteretic damper that forms the central part of the Panels. If damaged by an earthquake, the dissipative element can be replaced in situ by a new one.

Dissipation Panels are compatible and can be easily integrated into existing structures, preserving the original structural scheme. The proposed system also corresponds to a reversible intervention solution with reduced interference with the existing construction. Therefore, the Dissipation Panels are a low intrusive solution that may be particularly interesting for seismic behavior enhancement of historic buildings.

Full-scale prototypes of the Dissipation Panels were produced and tested in order to characterize its cyclic behavior. Experimental results are summarily presented. Design and analysis of a historic *Pombalino* building, incorporating such proposed damping technology are also discussed. *Pombalino* buildings correspond to the typology of construction that was used in the reconstruction of Lisbon after the well-known catastrophic earthquake of 1755. One of the most remarkable features of such buildings is their structural concept, which was significantly innovative at that time. It included the notable timber framed walls, whose role inspired the conception of the Dissipation Panels.

Keywords: Dissipation Panels; energy dissipation; damper; seismic retrofitting; low intrusive solution.

1. Introduction

Current approach to enhance the seismic protection level of a building assumes global distribution of damage in the structure. However, deformations can be reduced if the quite recent seismic protection systems (energy dissipation and seismic isolation systems) are installed into the structure.

Innovative Dissipation Panels for seismic retrofitting of buildings are under development. The design of the Dissipation Panels was based on the role of the historic timber framed walls as well as on the incorporation of an energy dissipation system, which enables to reduce damage and limit losses more effectively than the traditional approach [1, 2, 3]. The new solution was designed to improve the seismic energy dissipation capacity of buildings while minimizing interference with their original structural concept. Besides the increase of damping, the herein presented system is aimed at implementing compatible, low intrusive and reversible retrofitting interventions. Basic characteristics of the constructions are hence preserved.

A series of cyclic tests to evaluate the performance of full-scale prototypes of the Dissipation Panels were carried out. Main experimental results are briefly described. Design and analysis of a historic building incorporating such proposed damping technology are also discussed.

2. Description of the Dissipation Panels

Basic conception of the Dissipation Panels corresponds to an articulated supporting frame with an embodied replaceable central damper. The frame is formed by two columns, a top and a bottom beam, and diagonal braces. The Panels are positioned like an interior wall between two consecutive floors of the building as schematically represented in Fig. 1.
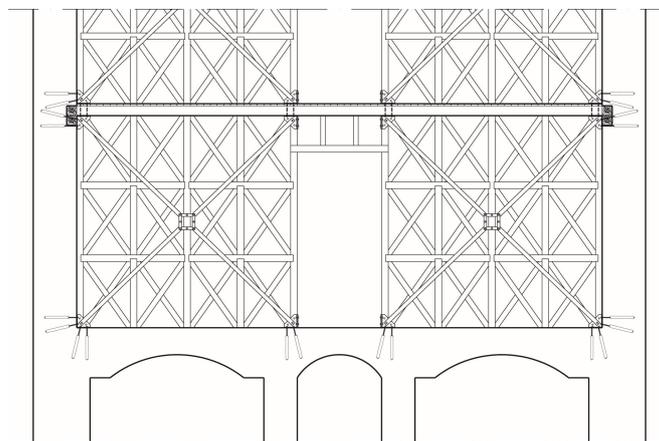

Fig. 1 – Schematic representation of the installation of the Dissipation Panels in an old structure.

All the elements that compose the Panels are made of steel as assumed for the initial design of the solution. The Panel was conceived to exploit the hysteretic behavior of the damper. The damper, as the main and central part of the Panel, has a very simple geometry and was conceived to take advantage of the plastic behavior of steel. The inelastic behavior is limited to the damper, where plastic hinges are formed. Damage is thus concentrated in a device that can be easily replaced if necessary. Ductility of the structure is achieved through means of making the supplemental damping device to yield, so that the rest of the structure is protected from damage. The dampers are easy to handle and to connect to the steel members of the supporting bracing system so they can be effortlessly changed over from one damper to another.

The Dissipation Panels are compatible and easily adaptable to common structures and no structural demolitions are necessary. The technology is reversible, which means it can be removed afterwards without

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causing damage to the original existing structure. Therefore, the technology corresponds to a low intrusive solution. This advantage can be particularly interesting for old/historic buildings. For example, as it is shown in Fig. 1, the Dissipation Panels can be integrated within/in respect of an existing structure that includes the notable *Pombalino* timber framed walls as part of its original structure [1].

3. Experimental Program

The experimental program was defined in order to evaluate the behavior of the Dissipation Panels under cyclic loading. The experimental tests originated, among other relevant information, the force-displacement curves that permit to identify the hysteresis cycles and quantify the capacity to dissipate energy of the proposed technology.

3.1 Specimens and experimental setup

The experimental program was divided in three phases. First phase corresponded to the determination of the mechanical properties of the materials that were used to produce the Dampers. Second phase consisted of the cyclic tests of the Dampers alone (full-scale; not incorporated in the Panels). Third phase of the experimental program comprehended the cyclic tests of full-scale prototypes of the Dissipation Panels. For each complete prototype of the Panels, it was fabricated an additional Damper, which was cut from the same steel plate. The characterization of the Dampers corresponded to the second phase of the experimental program. Designation adopted for the tests specimens presented in this paper is detailed in Table 1. The tests were realized at the Laboratory of Structures and Strength of Materials at Instituto Superior Técnico (LERM/IST).

Table 1 – Designation of tests specimens

Dampers tests	Panels tests	Notes
DHJ1	P4DHJ2	Damper DHJ1 and damper of Panel P4DHJ2 were cut from the same steel plate.
DHW1	P5DHW2	Damper DHW1 and damper of Panel P5DHW2 were cut from the same steel plate.
DHF1	P6DHF2	Damper DHF1 and damper of Panel P6DHF2 were cut from the same steel plate.

The cyclic tests of the Dampers were carried out in a universal Instron testing machine as shown in Fig. 2. Displacement along the direction of the force was measured with a linear transducer. In some specimens, extensometers and photogrammetry were also part of the instrumentation.

The Panels were subjected to cyclic quasi-static tests performed in the reaction wall of the LERM/IST as presented in Fig. 3. The tests involved the application of controlled in-plane horizontal cyclic displacements at the top of the models by a 400mm stroke mechanical actuator with 1000kN capacity that incorporated a load cell in order to measure the applied load. The bottom horizontal component of the Panels was fixed to an auxiliary steel beam of the laboratory. The displacements of this beam were restrained through its connection to the floor of the laboratory. In order to guarantee the stability of the Panel during the test, a top guiding system that restrained its transversal displacement was used as it can be observed in Fig. 3.

The instrumentation of each Dissipation Panel consisted of: 2 extensometers in each diagonal member of the Panel; 2 extensometers in each vertical element of the Panel; 1 draw wire transducer at the top of the Panel with a maximum measuring capacity of 500mm. The control of the amplitude of the displacement cycles (dh) was done through this latter measuring device. Figure 4 shows a detail of the instrumentation of the central Damper device belonging to the Panels tests: 2 Linear Variable Differential Transducers (LVDTs) (with 25mm course), D1 and D2, and 8 extensometers (for this second set of tests, extensometers in the central damper were only used for the model P5DHW2). In specimen P6DHF2, photogrammetry was also used as an additional method of instrumentation to obtain the displacements of the Panel along the cycles.
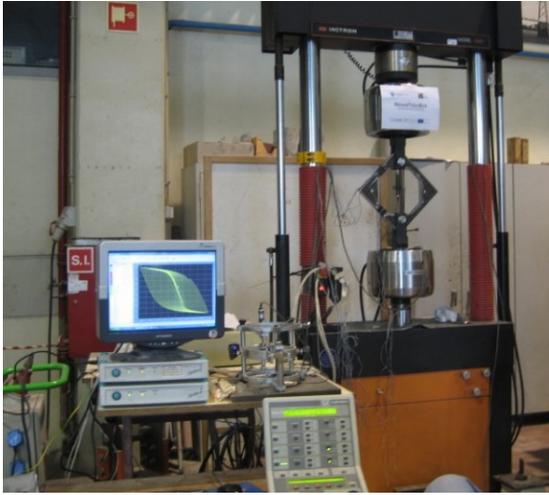
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Fig. 2 – Experimental setup for testing the Dampers.

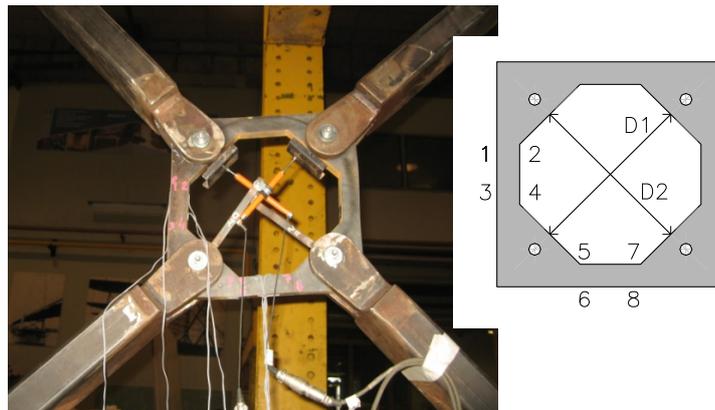Fig. 3 – Experimental setup for testing the Dissipation Panels.

Fig. 4 – Instrumentation of the damper of Panel P5DHW2. Transducers D1 e D2 and extensometers 1 to 8.

The scheme of the horizontal displacements (d) imposed to the prototypes of the Panels during the cyclic tests is displayed in Fig. 5. For each model, the imposed horizontal displacements corresponded to increasing amplitudes at each cycle. The horizontal displacement history was defined based upon the specifications of the standard EN 15129:2009 – Anti-seismic devices [4]. The tests were performed until the complete failure of the specimens.

The set of specimens presented in this paper (Table 1) correspond to the second series of the experimental program. First series of the tests are disclosed in [5]. Same setup and experimental procedures were adopted in both series. In the first set it was detected that there were looseness connections between the different elements that form the frame of the Panels. When reversing the direction of the cycles, the lateral displacement increased without increment of the horizontal load. In the second series of the program, the constructive looseness connections were significantly reduced.
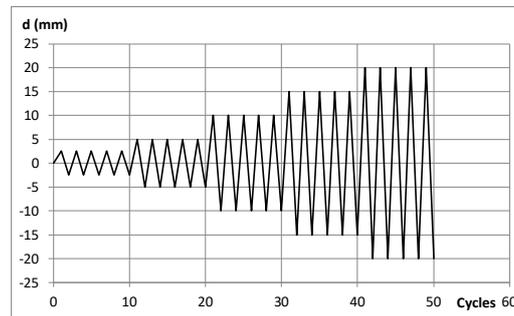
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Fig. 5 – Imposed horizontal displacements in the tests of the Panels.

3.2 Tests results and discussion

3.2.1 Dampers

The experimental diagrams of the cyclic tests of the Dampers are presented in Figures 6 to 8. For the three specimens, the curves show similar hysteretic stable behavior, without any sign of degradation of both stiffness and strength, and a good dissipation energy capacity. Comparing the diagrams of the three models, the highest post yield stiffness was obtained in the DHF1 model and the lowest value of this property corresponded to the DHW1.

Throughout each test it was possible to observe the deformation of the Damper and the formation of plastic hinges in the interior angles, where the rupture occurred, as shown in Figures 6 to 8. All the specimens exhibited an identical behavior.
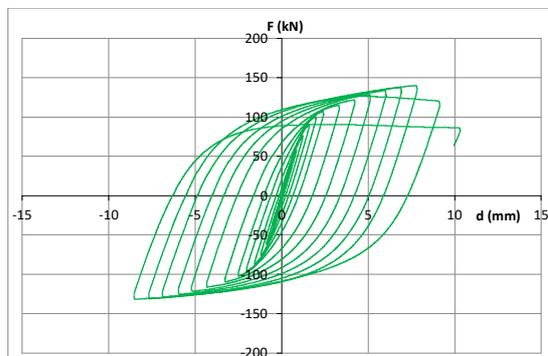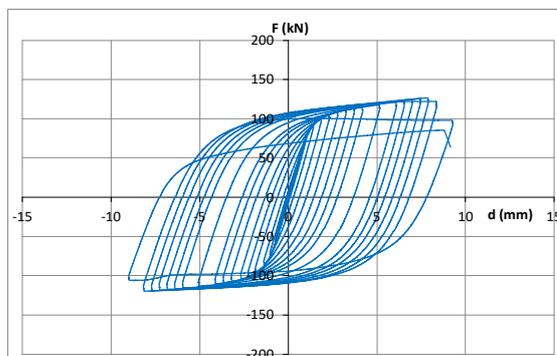

Force-Displacement Diagram   Failure of specimen

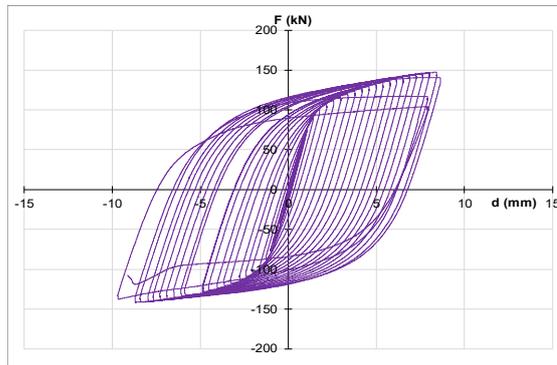Fig. 6 – Cyclic test results of DHJ1 specimen.
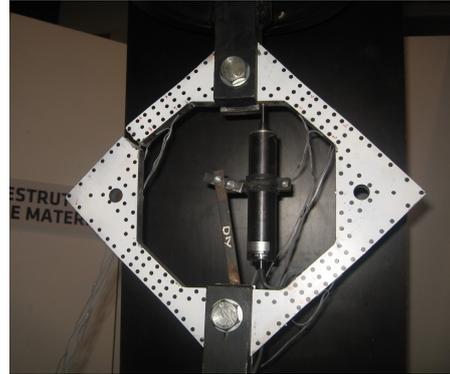

Force-Displacement Diagram   Failure of specimen

Fig. 7 – Cyclic test results of DHW1 specimen.

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| Force-Displacement Diagram | Failure of specimen |

Fig. 8 – Cyclic test results of DHF1 specimen.

3.2.2 Dissipation Panels

The Panels were subjected to cyclic quasi-static tests performed in the reaction wall at the Laboratory of Structures and Strength of Materials at Instituto Superior Técnico (IST) as shown in Fig. 3. The main results correspond to the hysteretic diagrams of the Dissipation Panels presented in Figures 9 to 11. In these Figures is shown, in the left side, the horizontal force-displacement curve (Fh, dh, measured at the top of the Panel) and in the right, the diagonal force-displacement diagram (as per the diagonals directions of the Damper, D1 and D2). From the experimental horizontal force-displacement curves, it is possible to determine relevant data such as ultimate displacement, stiffness and dissipated energy. The results of the Damper allow to measure its dynamic behavior when incorporated in the Dissipation Panel and to relate them with the data obtained in the tests of the Dampers alone.

Similar main results were obtained for the here presented tested specimens. The experimental load-displacement diagrams show a good and stable cyclic behavior, with growing load-displacements amplitudes from one cycle to the next. The model P6DHF2 suffered rupture in a cycle of greater amplitude (dh = 20mm) than in the case of models P4DHJ2 and P5DHW2 (dh = 15mm). However, the P6DHF2 model only supported a full 20mm cycle. Note that it was not possible to obtain the values of the transducers of the damper of Panel P6DHF2 until the end of the test, because during the test, the transducers got out from the correct measurement position.
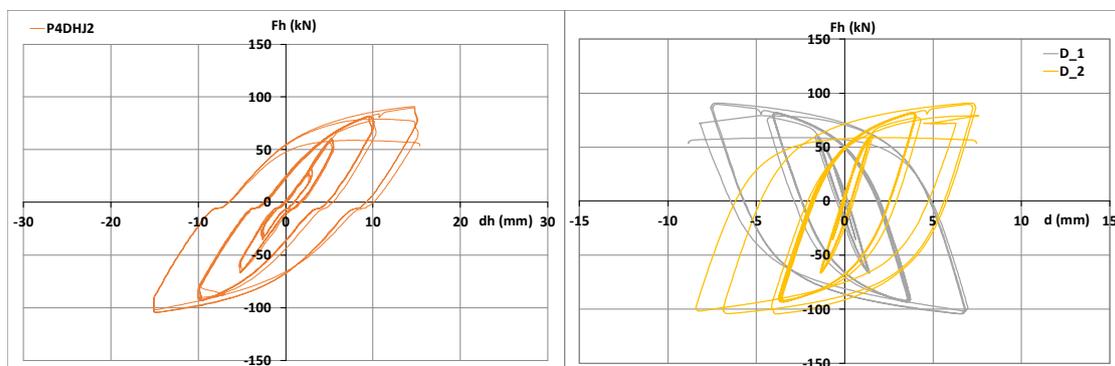

Fig. 9 - P4DHJ2 model test results. Horizontal Force-Displacement curve of the Panel. Horizontal Force-Diagonal Displacement curve of the Damper.
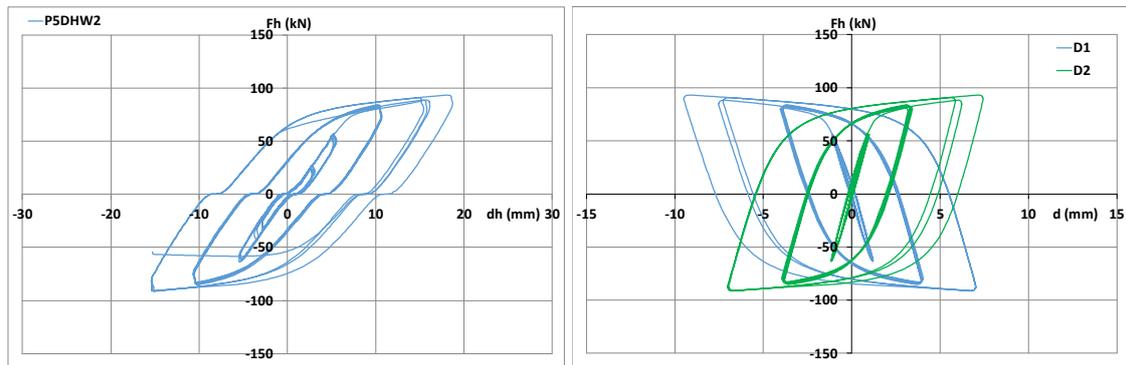
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Fig. 10 – P5DHW2 model test results. Horizontal Force-Displacement curve of the Panel. Horizontal Force-Diagonal Displacement curve of the Damper.
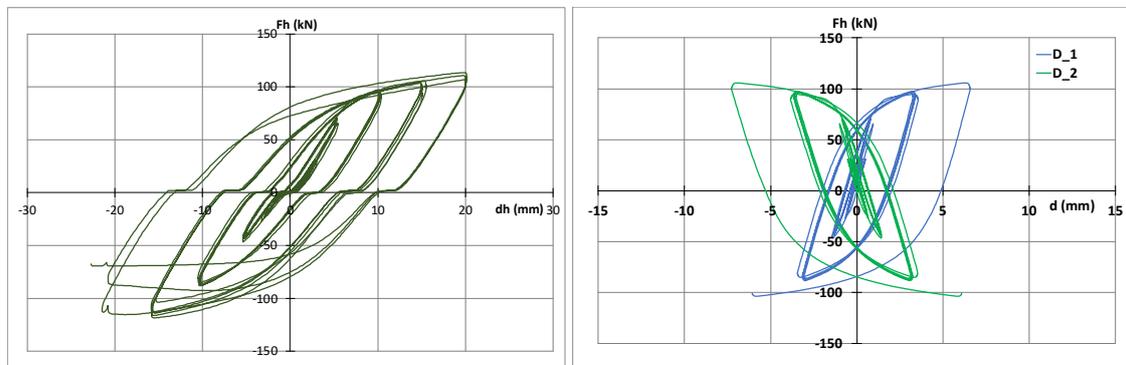

Fig. 11 – P6DHF2 model test results. Horizontal Force-Displacement curve of the Panel. Horizontal Force-Diagonal Displacement curve of the Damper. (Note: in this test, the transducers of the Damper were positioned in a symmetric way in relation to Fig. 4)

During the tests it was possible to observe the deformations of the dampers in each cycle and its growing amplitude until failure. The failure modes of the P5DHW2 and P6DHF2 specimens are shown in Fig. 12. For the three tested models, failure occurred due to rupture of the central dampers, which happened at the interior angles of the cross section. All of the others elements that formed the Panels exhibited a clear elastic response, below the yield limit of steel, as from the data collected from the strain gauges installed in the referred elements. As expected, damage was concentrated in the dampers, which could be easily replaceable after each test.
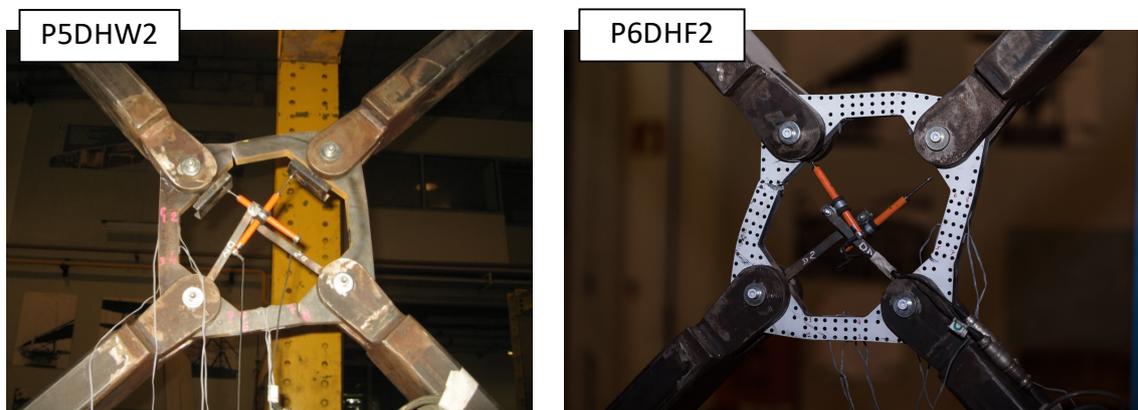

Fig. 12 – Failure of models P5DHW2 and P6DHF2.

The energy dissipated (ED) in each cycle corresponds to the area enclosed by the load-displacement curve. It represents the amount of energy dissipated during the cyclic loading associated with the hysteretic behavior. The equivalent damping coefficient for a given single cycle may be estimated based on Eq. (1)

$$\xi_{eq} = \frac{ED}{2\pi F_{max} d_{max}} \tag{1}$$

where ED is the dissipated hysteretic energy, F_{max} is the peak force and d_{max} is the maximum displacement [6]. The energy dissipated in each cycle and the equivalent damping that resulted from the tests of the Panels are presented in Fig. 13. It can be observed that the energy dissipation evidenced a considerable increase throughout each cycle. This trend is also noticeable for the equivalent damping ratio, since it also increases from the beginning of the loading until the Panels reach its ultimate lateral strength.
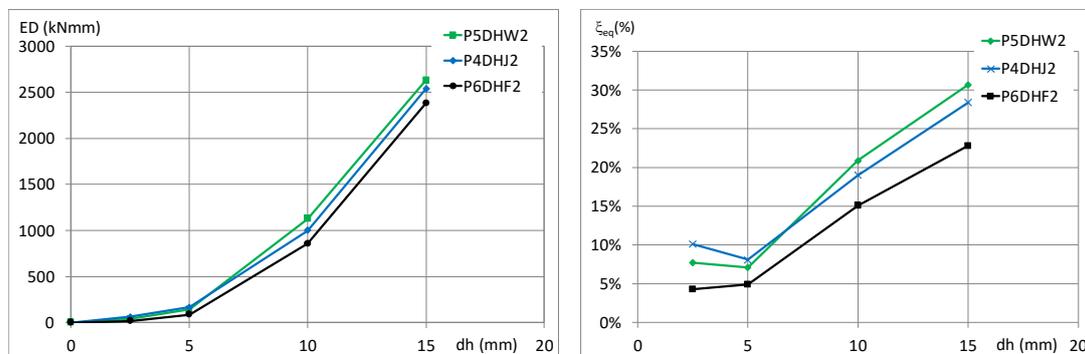
Fig. 13 – Dissipated energy and equivalent damping.

Results of P4DHJ2 e P5DHW2 tests do not significantly differ in terms of the principal parameters evaluated, such as ultimate displacement, energy dissipation and equivalent damping ratio. In the case of the P6DHF2 specimen, the values of dissipated energy and equivalent damping are lower than the results of the models P4DHJ2 and P5DHW2. This difference is mainly attributed to the higher rigidity of the model P6DHF2 in relation to the other two models.

Comparing the herein presented results and the formerly tests Paula et al. (2016) it can be observed that the correction of the constructive looseness connections lead to considerable improvement of the hysteretic behavior of the Panels. The damping ratio provided by the Dissipation Panels specimens is superior to 20% at a displacement of 15mm. Considering this displacement to be acceptable for the interstorey drift for building structures to remain elastic or experience minor damage under severe seismic actions, the Dissipation Panels can be used to control deformations and protect structures.

4. Application to an ancient building

4.1 Characterization of the building

The building is part of a Pombalino block located in the downtown of Lisbon. Pombalino buildings correspond to the typology of construction that was used in the reconstruction of Lisbon after the destructive earthquake of 1755 (the great mentor of the reconstruction of Lisbon after the disaster was Marquis of Pombal). In a completely new way in Europe, anti-seismic provisions were introduced in a deliberate and systematic manner and at a city scale level. One of the most remarkable features of the buildings is their structural concept, the distinctive gaiola system, which was designed to provide the buildings with adequate seismic behavior, enabling them to resist horizontal loads. The gaiola system consisted of an interior 3D timber grid mainly formed by the timber framed walls (frontal walls) and the floors. These structural elements were supposed to be connected to the main stone masonry exterior walls by a set of timber members embedded along the inner face of the masonry walls. Further bracing to the two-directional vertical

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bracing system of the timber framed walls was provided by the timber floors and roof timber trusses. The gaiola designation was coined because the building seemed like a bird cage, with the carpentry work high up in the air.

The timber structure of the frontal walls consisted of a skeletal frame of vertical columns and horizontal beams braced with diagonals named St. Andrew's Crosses. The empty spaces of the walls were filled with rubble masonry made of small stones and ceramic elements recovered from the ruins of the earthquake, assembled with lime mortar. Several basic configurations of the frontal bearing walls have been identified in Lisbon old buildings. Timber species used in these buildings and their cross-section dimensions also present some variation.

The case study building has a rectangular plan layout of about 14m×21m and has five elevated stories and an attic (Fig. 14). The building is located at the corner of the block, so the main resistant masonry walls are composed of two principal facades (with openings that define the geometry of the masonry structural elements) and two party walls parallel to the facades. In the longest direction of the building, the party wall only corresponds to approximately half of its length. The other half of the masonry wall of the building is not shared with other buildings of the block. The thickness of the masonry external walls ranges between 40cm and 100cm, decreasing with the elevation of the building. Timber beams of the floor have sectional dimensions of 10-12cm×16-18cm, spaced about 40cm in plan.
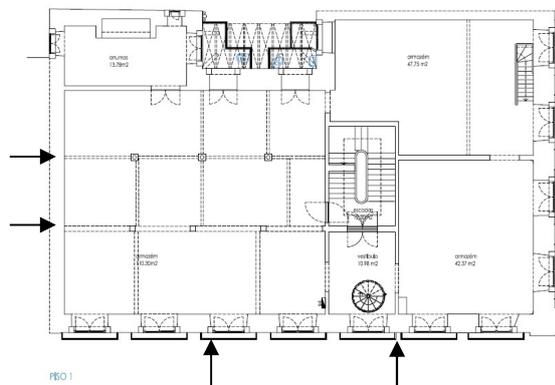

Fig. 14 – View of the case study building. Plan of Floor 1. Original location of the timber framed walls (frontal walls).

A survey of the actual condition of the building indicated that it had undergone considerable modifications with time. Major changes detected in the building were related to the significant removal (partly or totally) of most of the supporting interior frontal walls and addition of steel elements in some cases – Fig. 15. Other observed anomalies were localized timber decay, corrosion of steel elements and cracking of diverse elements.

The timber elements are generally in good condition, although some rot was detected, especially in the upper floors and near the openings through which the cyclic presence of infiltration water leads to wetting-drying cycles and consequently to the deterioration of timber. Decay and significant reduction of section were thus the most frequent anomalies that have been detected on the timber elements. Excess of deformation of some parts of the floors were also detected, probably due to stiffness and strength reduction of the timber sections. Generalized cracking of the walls and ceilings was attributed to movement and deflection of the supporting elements, disconnection of perpendicular walls or even excess of loading.

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Fig. 15 – Modification of the original structure. Incomplete frontal wall. Total removal of frontal wall and addition of steel elements.

4.2 Seismic analysis

A 3D numerical model was developed to perform the analysis of the case study building and assess its seismic performance. The exterior masonry walls were simulated by finite elements with isotropic behavior. For the representation of the timber floors and the interior frontal walls, frame elements were used. A specific weight of 22kN/m^3 was assumed for the characterization of the masonry. The modulus of elasticity for the masonry was calibrated taking into account the results of dynamic identification tests that were done in the building. Damping ratio was assumed to be equal to 5%.

The dynamic identification experimental campaign was performed in the second and fourth floors of the building. The natural frequencies that were identified related to the first modes were approximately equal to 1.0Hz, in both X (longest direction of the building) and Y (perpendicular to X) directions – Fig. 16. Other modes were also detected for frequencies between 2,5 and 2,7Hz, in X and Y directions, respectively. After the complete definition and calibration of the model, a seismic analysis was performed. Seismic action was defined by means of an acceleration response spectrum.
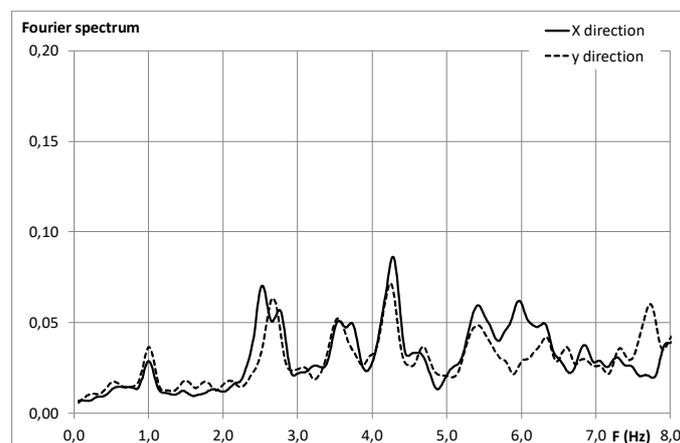

Fig. 16 – Dynamic identification test. Fourier spectrum result. 4th Floor.

4.3 Conservation and seismic retrofitting strategy

Proposed criteria for the rehabilitation is based on the assumption that the historic features and original materials of the building are of primary importance [3, 7, 8]. The works have to preserve the distinguishing characteristics of the structure and respect, as far as possible, the integrity of the designer's original structural concept. The removal or alteration of any element should be avoided. The strategy defined for the

intervention shall follow two base lines: preservation and repair of all of the existing original structural elements and structural reinforcement in view of increasing lateral seismic stability.

First objective can be achieved through maintaining the existing resistant elements such as the masonry walls, frontal walls and the timber floors and roof. For these elements, decayed and missing sections should be restored to their original configurations [9, 10].

As part of the seismic retrofitting strategy, it is proposed to install the Dissipation Panels. These elements are installed as interior walls, perpendicular to the main exterior masonry walls and adequately connected to them. The Dissipation Panels are supposed to be located in the same alignments where the original frontal walls (that had once been an important part of the structure) were originally positioned and from where they have been removed – Fig. 17. This should allow the reestablishment of the original structural concept but with a more seismic strengthening effective system. The panels are planned to be installed along the two principal directions of the building, parallel to the X direction and to the Y direction.

For the analysis of the dynamic behavior of the building within the introduction of the Dissipation Panels, hysteretic representative simulating elements are added to the 3D model of the building. To incorporate a non-linear displacement device into a numerical structural model, the experimental force-displacement loops of steel hysteretic devices are usually approximated by a hysteresis curve with an initial stiffness (k1), a post yield stiffness (k2) and a yield force. The dampers – the dissipative parts of the system – are modeled to deform and to dissipate energy, while the other parts that form the system shall remain elastic. The hysteretic elements are calibrated according to the experimental results.

Preliminary outcomes are encouraging. Nevertheless, the efficiency of the solution needs a complete evaluation in terms of maximum interstorey drifts and masonry stresses, among other parameters that characterize the seismic performance of a structure.
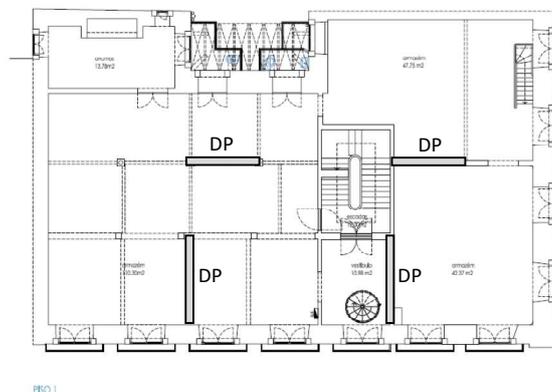

Fig. 17 – Plan of floor 1. Possible locations of the Dissipation Panels (DP).

5. Conclusions

This paper presented mains results of the development of Dissipation Panels for seismic retrofitting of buildings. The Dissipation Panels correspond to a passive seismic protection solution, which when incorporated into a structure, will allow the control of deformations due to earthquakes, through the dissipation of energy concentrated in a damper. Full-scale cyclic tests were carried out in order to evaluate the energy dissipation capacity of the proposed solution. Essential outcomes of the experimental study indicate that the damping device have a good energy dissipation capacity. The test results are being used for the calibration of numerical models representative of the behavior of the Panels. The seismic response of a building retrofitted with the Dissipation Panels is also under development.

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6. Acknowledgements

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