Seismic retrofitting of Pombalino “frontal” walls

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SUMMARY:
The “pombaline” structure has a good seismic behaviour, though after more than 250 years these buildings need rehabilitation works because of their degradation, of the inadequate interventions they have been subjected to (such as adding storeys, modifying structural elements or changing the functionality of the buildings) and because of the new codes’ more demanding rules for earthquake resistance. The research presented in this paper aimed at experimentally characterizing the cyclic behaviour of “pombaline” frontal walls reinforced with three different methods. The reinforcing methods consisted of (i) dampers on diagonal braces; (ii) reinforcement of timber connections with steel plates; (iii) application of a reinforced rendering.

Keywords: Pombaline; Reinforcing; dampers; steel plates; reinforced rendering.

1. INTRODUCTION

After the large destruction of Lisbon due to the 1755 earthquake, the city had to be almost completely rebuilt. The innovative “pombaline” buildings were then developed. This type of building is characterized by its structural interior “frontal” walls in elevated floors, constituted by a timber frame with vertical and horizontal elements, braced with diagonal elements (Saint Andrew’s crosses) with a masonry infill. These timber elements were connected to the floors’ structure, forming a three-dimensional timber frame with improved stiffness and deformation capacity under seismic actions. Most of these buildings presently need to undergo seismic rehabilitation due to the following reasons: (i) their natural degradation with time; (ii) the need for adaptation to the present serviceability conditions, generally involving structural changes; (iii) former interventions with elimination or damaging of structural elements, affecting seismic resistance; (iv) the noncompliance with the new generation of seismic codes (Appleton, 2003) (Mascarenhas, 2005).

Due to the lack of specific codes the seismic rehabilitation of old buildings is usually carried out based on empirical rules, essentially depending on expertise and experience of designers and contractors. The lack of knowledge of the “pombaline” walls’ seismic behaviour and of the effect of possible reinforcing solutions led to the absence of design procedures for seismic rehabilitation that could be accepted. The main objective of this project is to contribute to the development of knowledge in the area of seismic rehabilitation and reinforcement of “pombaline” buildings.

2. EXPERIMENTAL PROGRAMME

2.1. Objectives

The experimental work on frontal walls comprised two parts. The first part consisted of an experimental campaign to assess the in-plane seismic behaviour of “frontal” walls and to evaluate the effect of its components (timber frame, masonry). The second part aimed at evaluating the adequacy and efficiency of three proposed seismic rehabilitation methods based on buckling restrained dampers, steel plate reinforcement on timber elements' connections and reinforced render. In this paper only the second part of the experimental campaign will be presented.

2.2. Test specimens

The tested walls are constituted by four Saint Andrew's crosses. A total of ten walls were constructed and tested in the laboratory. The tests of the first part of the experimental work were performed on two modules of Saint Andrew's crosses made of timber without masonry infill, referred to as timber frames, and two identical modules with masonry infill, referred to as masonry walls. The remaining modules were built with masonry infill and using seismic rehabilitation methods based on buckling restrained dampers, steel plate reinforcement and reinforced rendering. Table 2.1 indicates the performed tests.

Table 2.1. List of tests in this experimental work

Wall	Number of tests	Labelled	Part
Timber frame	2	TF1, TF2	First
Timber-masonry wall	2	MW1, MW2	First
Timber-masonry wall with BRD	3	MW4, MW5	Second
Timber-masonry wall with steel plates	2	MW6, MW7	Second
Timber-masonry wall with reinforced render	1	MW8	Second

The characteristics of the walls' construction and the description of the experimental procedures on test are presented in a companion paper to this Conference (Gonçalves et al., 2012).

3. BUCKLING RESTRAINED DAMPERS

The reinforcement of Pombaline walls and particularly the increasing capacity of energy dissipation can guarantee an improvement of the building seismic behaviour. The reinforcement adopted aimed at strengthening this structure with an economical and feasible system , so as to make it usable in practice. An elastic-plastic steel damper was studied in this project, consisting of steel bars and rods which ensures increased energy dissipation. These dampers operate along a diagonal of the walls. Following the design described by Kumar *et al.* (2007), the damper was assembled, but on a small scale.

3.1. Characterization of damper

The damper was composed by a steel rod (8 mm diameter 55.5 cm length), laterally restrained by steel plates and profiles, according to the scheme presented on Figure 3. The rod has been fixed to a guiding bar, in which it can move freely, preventing the occurrence of bending out of the plane. The guiding bar has been welded in profiles UNP 100 (Figures 1 and 2).

Figure 1. Walls MW4/5 with damper

Figure 2. Guides, the rod and plate

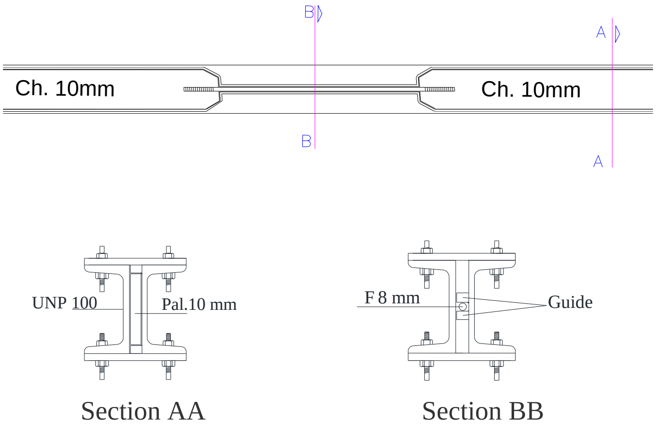


Figure 3. Scheme of damper

In order to obtain the mechanical properties of the damper, such as strength, elastic moduli and energy dissipation, cyclic tests were carried out in a universal Instron testing machine, at a load speed of 0.05mm/s (Figures 4 and 5). The results of the cyclic tests are presented on Figure 4 showing a good energy dissipation capacity. Observed an asymmetric behaviour in Figure 4, the maximum force of the damper is 25 kN, in tension, and 35 kN on compression. This difference is due to the construction of the damper, and the (controlled) buckling of the damper, what causes touch in the guides and increased force.

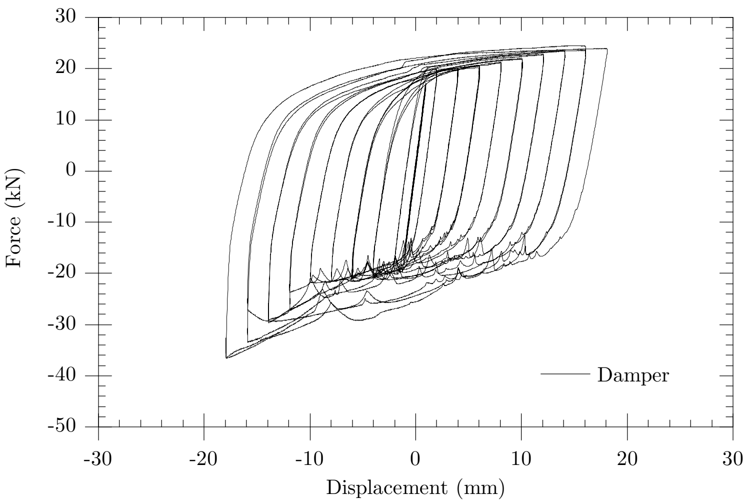


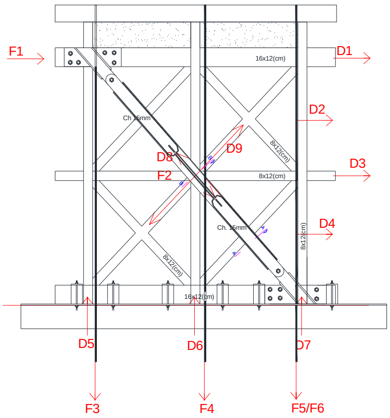
Figure 4. Cyclic response of the damper

Figure 5. Damper test

3.2. Results and discussion

The frontal walls reinforced with steel dampers placed diagonally in the structure were analysed. Figure 6 shows the location and orientation of the forces and displacement measured by instrumentation of walls MW4 and MW5.

a) Wall MW4/5



b) Schematic drawing of wall (MW4/5) instrumentation

Figure 6. Walls MW4 and MW5

The experimental work consisted of submitting the walls to increasing cyclic displacements until rupture. From the analysis of Figure 7 it is observed that the damper with the best performance was that installed on wall MW5.

Also in Figure 7 (right) it was observed energy dissipation on the first cycles of wall model MW4. During the test the guiding system welding collapsed and, as a consequence, the rod buckled. After the buckling of the rod no more energy dissipation occurred (Figure 8a).

The energy dissipation in the MW5 wall occurs both in tension and compression, as observed in Figure 7 (right). It is noticeable that the maximum displacement of the damper is 22 mm, in tension, and 15 mm on compression, due to the localized buckling which the rod shows under compression (Figure 8b). This results in better energy dissipation in tension than in compression phase.

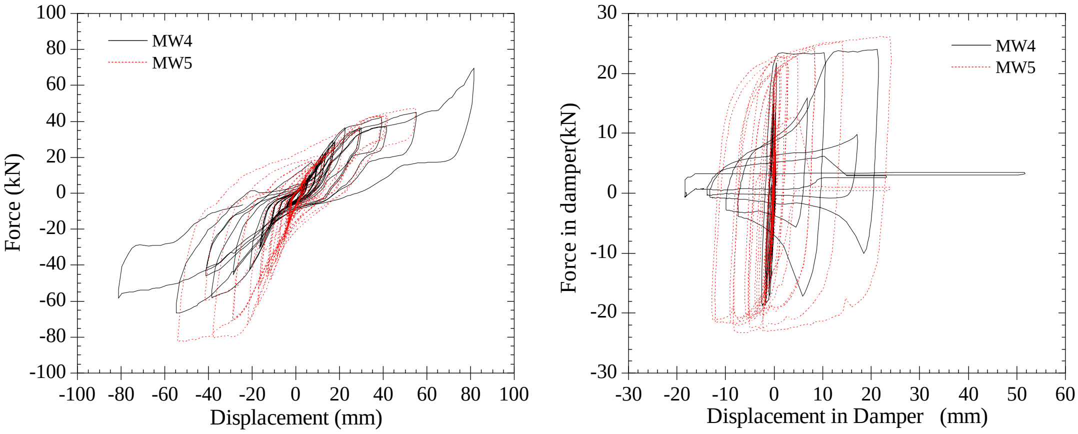


Figure 7. Comparison of damper

Figure 8 shows the welding failure in the test element MW4, compression (Figure 8a) and the (controlled) buckling of the damper in the test element MW5 (Figure 8b).

a) Rupture of the welding rod guide in MW4

b) Instability of the rod damper in test MW5

Figure 8. Rupture and instability of the damper

The load-displacement curves of tests MW1 and MW5, respectively unreinforced wall and wall reinforced with damper, are shown in Figure 9. The maximum strength values are 82.3 kN for the reinforced wall and 46 kN for the masonry wall, measured at the displacement of 55 mm, corresponding to a 2.6% drift.

The energy dissipated in each cycle may be evaluated by calculating the area within the load-displacement curve. It can be concluded that the damper has a good capacity to dissipate energy, although in the force-displacement curves (MW1 and MW5) the area of cycles of compression are smaller, which is due to the localized buckling which the rod shows in compression. This phenomenon leads to increased difficulty in obtaining a symmetrical behaviour (tension and compression), which can be solved by placing two dampers in both diagonals (different wall faces). This implies, however, an increase in wall thickness, which would be a disadvantage of the solution.

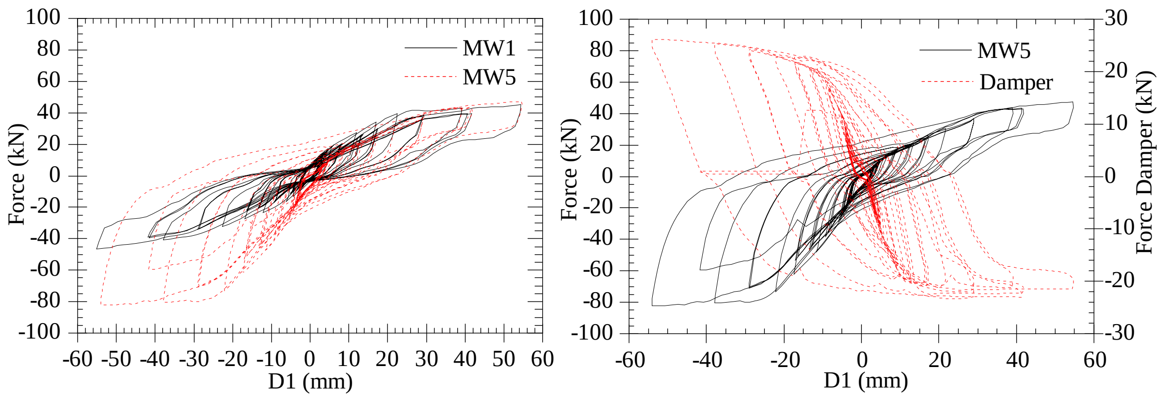


Figure 9. Force-displacement curves for MW5 and MW1

4. STEEL PLATE REINFORCEMENT

Two walls with reinforcing steel plates were tested (MW6 and MW7). The plates were placed in all cross-having joints. The plates were designed to reinforce the connections, providing more strength and stiffness but still ensuring deformation capacity. Figure 10 shows the dimensions of the different plates, with a thickness of 3mm.

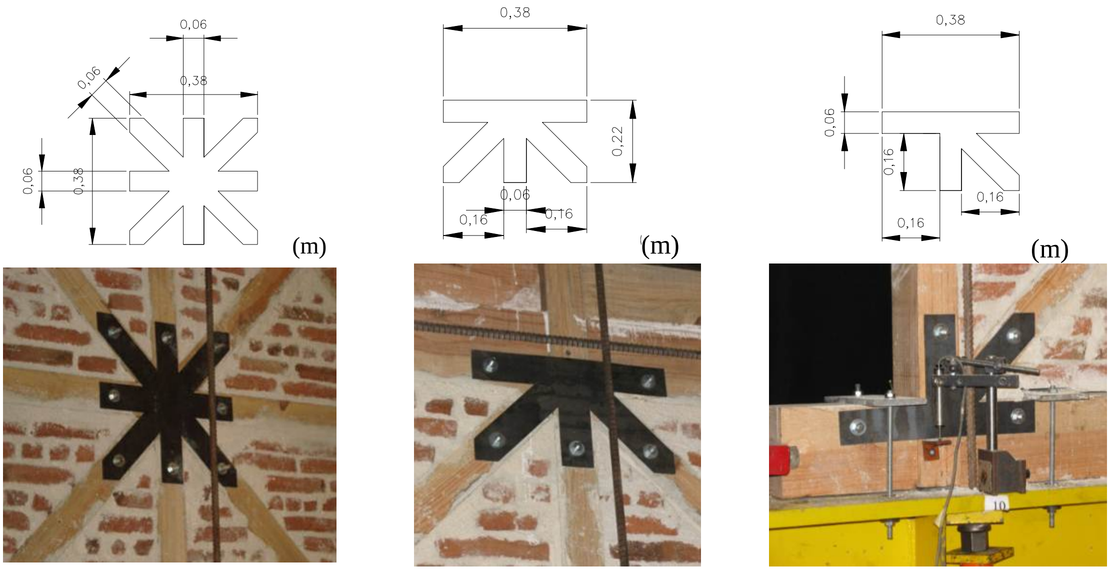


Figure 10. Steel plate reinforcement

4.1 Characterization of the plates

In order to obtain the mechanic properties of the studied material, such as strength and elastic moduli, tests were performed on specimens according to the NP EN 10 002-1 (Figure 11). The tests were carried out in a universal Instron testing machine, at a load speed of 0.05 mm/s (displacement between grips). The stress-strain profile of the plate is presented in Figure 12.

Figure 11. Specimens

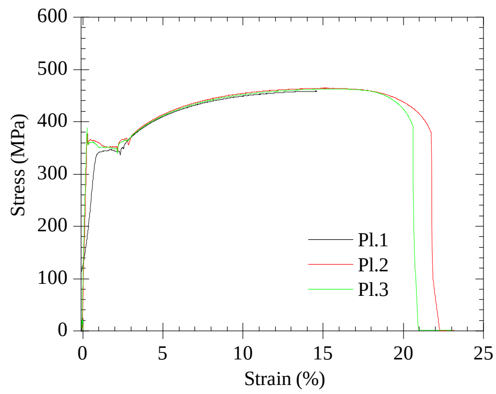
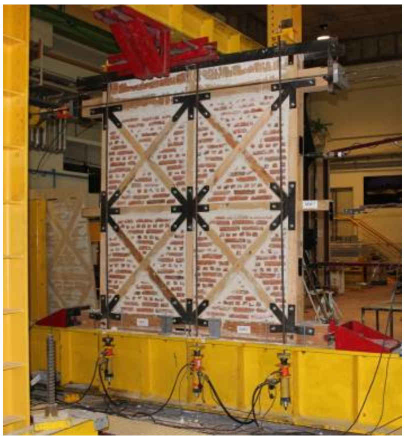


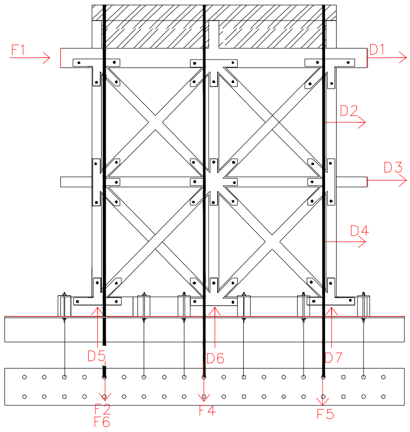
Figure 12. Stress-strain response for plates of 3 mm

4.2 Results and discussion

Figure 13 represents the location and orientation of the forces/displacement measured by instrumentation of the walls MW6 /7.



a) Photo of Wall MW6



b) Schematic drawing of walls (MW6/7) instrumentation

Figure 13. Walls MW6/7

As expected, the behaviour of the walls with reinforcing plates resulted in an increased stiffness and energy dissipation (Figure 14). At a displacement of 54 mm, a force of 109 kN was obtained in the reinforced walls (MW7 and MW6) and a force of 46 kN in the unreinforced wall.

Comparing the progress of the walls' hysteresis curves, it appears that the connection of the timber elements promotes an increase of the energy dissipation from the beginning of the test, taking advantage of the geometry of the wall for this purpose.

The boost in the wall's stiffness occurred for displacements higher than about 60 mm is due to the increase of force in the tensioned cables, when their jacks reach their limit course and they start to operate as tie rods.

The major conclusions drawn from the results obtained in the walls with reinforced plates (MW6 and MW7), in comparison with the wall without reinforcements (MW1), are: i) load increased for the same displacement, which leads to higher stiffness; ii) the energy dissipated in each cycle increased, which implies a better behaviour when subjected to an earthquake load.

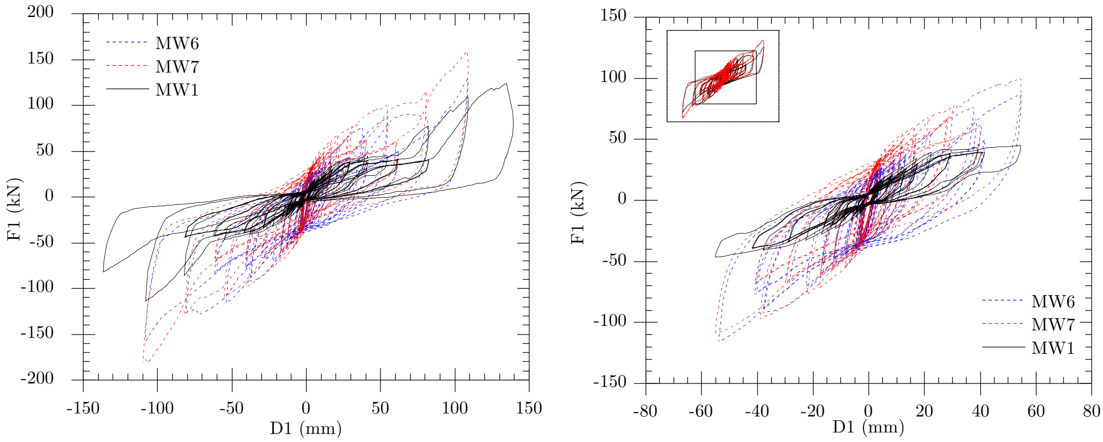


Figure 14. Force-Displacement curves for MW6/7 and MW1

5. REINFORCED RENDER

The application of reinforced render is a relatively simple technique that has been used in the rehabilitation of walls of old buildings. The study sought to evaluate the influence of this type of solution in the resistance and energy dissipation capacity of the frontal wall. The implementation of reinforced render applied on both sides of the wall MW8 (Figure 15) comprised the following stages:

i. Application of mortar , approximately 2 cm thick;
ii. Placement of metal mesh stretched ridge 20/25 galvanized;
iii. Fixing the metal mesh with nailing through-holes in staggered rows, one per meter, with threaded rods ø8 mm/1m,
iv. Finally, the application of the render with mortar, approximately 3 cm thick.

The reinforced mortar was applied on both sides of the wall.

a) Mortar with metal mesh (detail) b) Mortar with metal mesh

Figure 15. Reinforced rendering

5.1 Characterization of reinforced render

In order to obtain the mechanic properties of the studied material, such as strengths and elastic moduli, tensile tests were carried out on specimens with nominal dimensions of 500 x 450 x 50 mm (Figures 16/17). Tests were carried out in a universal Instron testing machine, at a load speed of 0.05 mm/s (displacement between grips). The stress-strain profile of the plate is presented in Figure 18, whose analysis shows that a 2.4 MPa (RA1) and a 1.8 MPa (RA2) was obtained for the Stress.

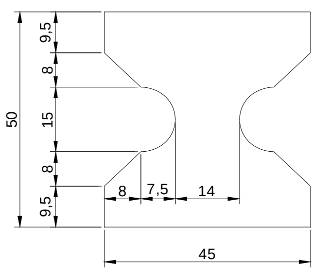


Figure 16. Specimen

Figure 17. Failure mode

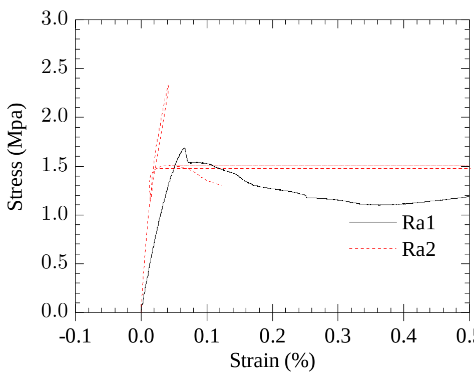
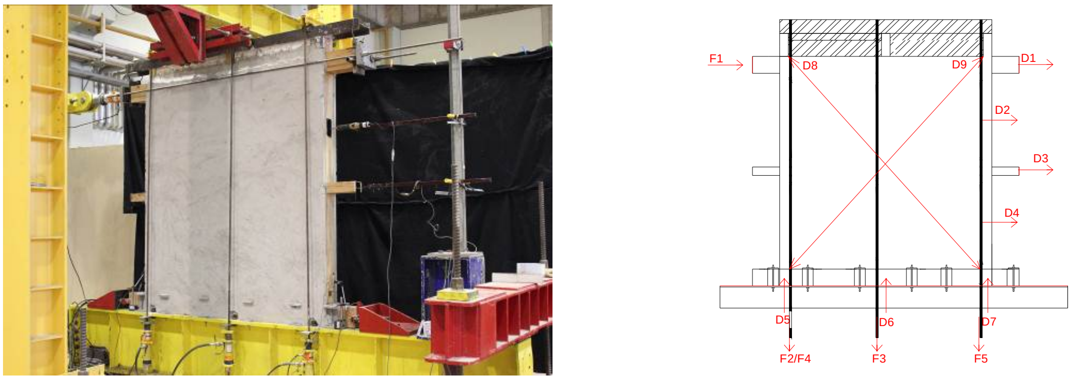


Figure 18. Stress-strain response for plate of 3 mm

5.2 Results and discussion

Figure 19 shows the location and orientation of the forces and displacement measured by instrumentation of wall MW8.



a) Wall MW8 b) Schematic drawing of wall MW8

Figure 19. Wall MW8

In the hysteresis' curves of tests MW1 and MW8, respectively unreinforced wall and wall with render reinforced with a steel mesh, shown in Figure 20, it is observed that the wall with reinforced rendering has an increased stiffness in the first cycles, until 10 mm of displacement. After that, the force remains constant because some cracking in the reinforced rendering starts to appear, leading to the loss of stiffness, but even though with higher capacity of energy dissipation.

The load-displacement diagrams show that for a 40 mm displacement of the force applied, there is approximately 60 kN and 40 kN to the reinforced wall and simple wall, respectively. The results show that this type of reinforcement is less efficient when compared to other reinforcements studied herein. The collapse mechanism of the wall with reinforced render results in a cut at the base, with a non-efficient use of the reinforcement system.

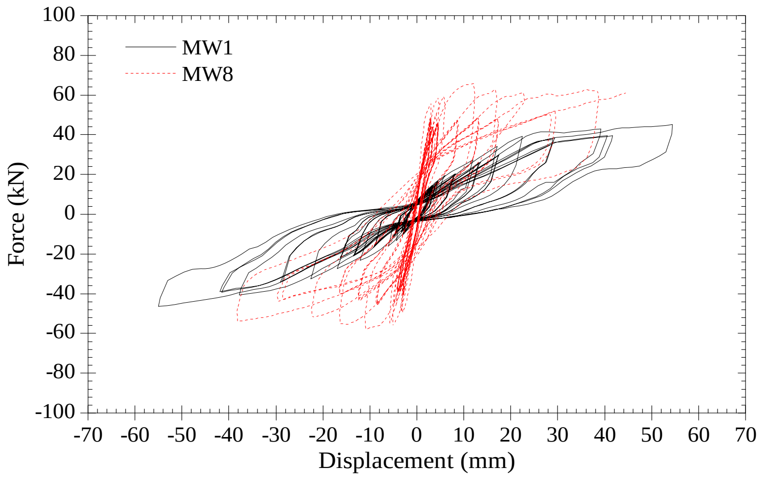


Figure 20. Curves hysteresis in walls MW8 and MW1

6. CONCLUSION

The conclusions of this study may be summarized as follows:

- According to the force-displacement curves, all reinforcement provided a higher ability to dissipate seismic energy, with an increase in their stiffness (Figure 21);
- The damper (MW5) had a good behaviour in tension but in the compression cycles some instability was observed, which leads to the conclusion that this system is difficult to implement when performing the rehabilitation;
- The walls with reinforcing plates (MW6 and MW7) showed the best behaviour in dissipating energy in the tension–compression cycles;

- The reinforcement with rendering system (MW8) led to an increase in stiffness of the wall, up to 10 mm of displacement. Then, the reinforcement started to crack at relatively constant load;
- The application of steel plates was the reinforcing technique that induced the best behaviour, with higher energy dissipation and the hysteretic cycle symmetry.

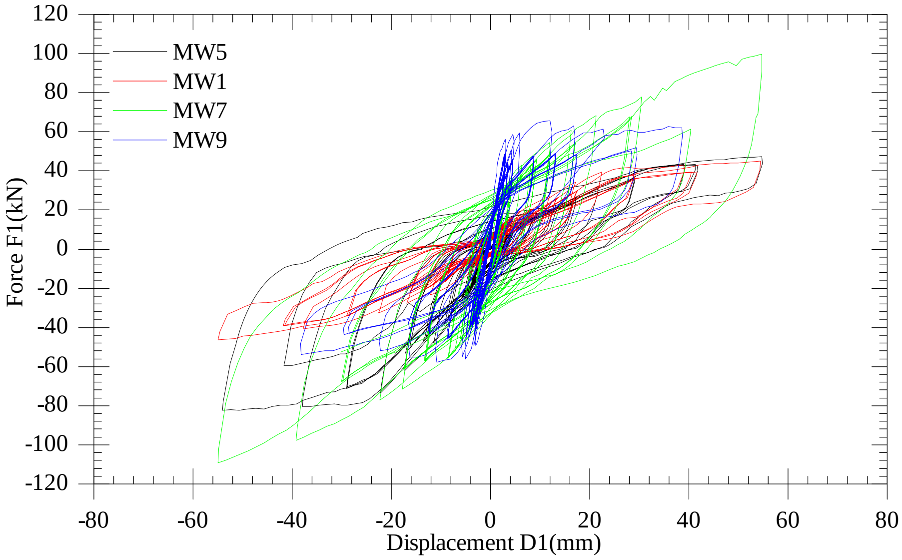


Figure 21. Curves hysteresis in walls MW1/5/7/8

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