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SEISMIC BEHAVIOUR OF TRADITIONAL HALF-TIMBERED WALLS: CYCLIC TESTS AND STRENGTHENING SOLUTIONS

Elisa Poletti[1], *Graça Vasconcelos*[2]

ABSTRACT

Half-timbered buildings represent an important historical heritage in many countries. They are diffused in various regions for different reasons, such as availability of materials, to lighten a structure, their low cost, the strength they offer and as a construction element able to resist seismic actions. This latter issue is the research topic analysed here, as half-timbered buildings have been specifically used in reconstruction plans as earthquake-resistant buildings in many countries, such as Portugal, Italy, and Greece. All these buildings were characterized by an internal timber skeleton constituted of vertical and horizontal elements and braced with diagonal elements (St. Andrew's crosses). This structure aimed at improving the global stability of masonry buildings, enhancing their capacity to dissipate energy during earthquakes.
The aim of this paper is to study the behaviour under cyclic loading of such half-timbered walls, with typical connections, materials and geometries encountered in existing buildings. In general, half-timbered walls act as shear walls and confer to the masonry structure a better seismic resistance than that provided by a traditional masonry wall. Cyclic tests were performed on traditional walls and their behaviour was studied in terms of ultimate capacity, deformability, energy dissipation and stiffness. Subsequently, the tested walls were retrofitted with traditional techniques in order to understand the influence of the reinforcement and to estimate its effectiveness, or lack thereof.

Keywords: Half-timber, Cyclic test, Traditional reinforcement, Dissipation of energy, Ductility

1. INTRODUCTION

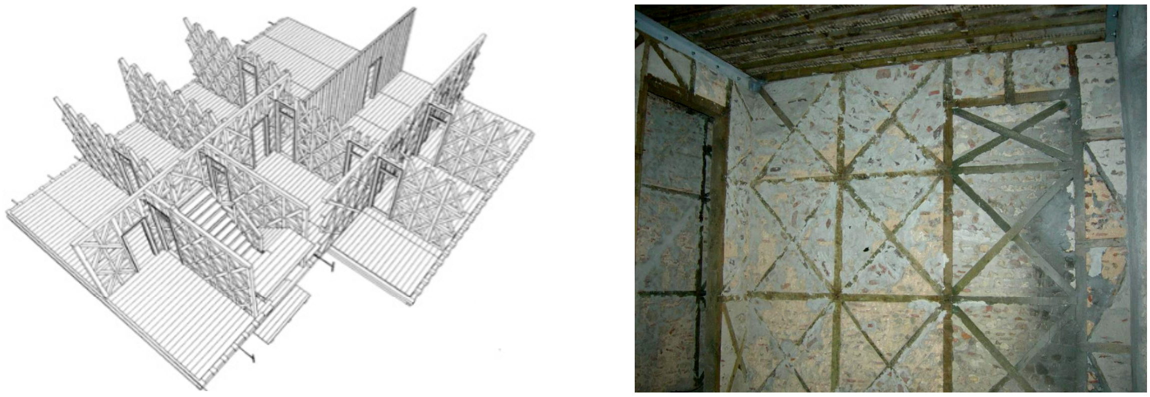
Half-timbered buildings have been a popular constructive system in many countries over the centuries. Masonry and timber are two of the most ancient materials used in construction and are easily available. The diffusion of these buildings makes their preservation of essential importance. The aim of this paper is to study the performance of half-timbered walls in their original condition and propose strengthening techniques.

1.1. Extension of half-timbered construction and historical importance

The origin of half-timbered structures probably goes back to the Roman Empire, as in archaeological sites half-timber houses were found and were referred to as Opus Craticium by Vitruvius [1]. But timber was used in masonry walls even in previous cultures (Mycean culture, Bronze Age) [2].
Traditionally, this type of structures was introduced as a seismic-resistant building. After severe earthquakes partially destroyed cities in the Mediterranean area (Lefkada, Reggio Calabria, Lisbon, Istanbul), new regulations [3-5] were introduced, which dictated how the new buildings should be built, introducing a bracing timber structure. But such buildings can be also found in non-seismic zones (UK, Scandinavia, Germany), due to the easily available materials that they adopt. Here too the buildings exhibit a timber frame, though the bracing members are less regular.
The example that is of most interest in this study is that of the reconstruction of Lisbon Downtown after the 1755 earthquake which destroyed that part of the city. The new regulations for the reconstruction of

[1] PhD Candidate, ISISE, University of Minho, Portugal, elisapoletti@civil.uminho.pt
[2] Assistant Professor, PhD, ISISE, University of Minho, Portugal, graca@civil.uminho.pt

the city introduced by Marques de Pombal included a building of usually five storeys with a stone masonry ground floor and an internal timber frame structure (named gaiola in Portuguese, which means cage) for the upper floors (Fig. 1a). The gaiola was linked to the external masonry walls through the timber floor beams, to which it was connected. A minimal timber skeleton was present also in the external masonry walls. The framing of the gaiola was characterized by the typical St. Andrew's crosses (Fig. 1b), which provided a bracing effect to the structure. The walls were filled with rubble or brick masonry. The internal half-timbered walls originally did not participate in the bearing of the vertical loads of the structure, the load bearing walls were the external masonry ones, but subsequent alterations or changes in use of the structure could have altered this condition.



(a) (b)

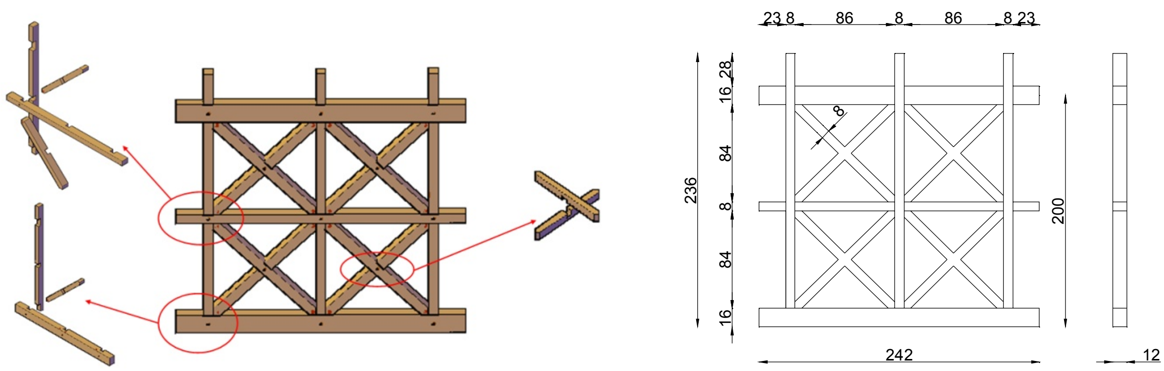
Fig. 1 Examples of gaiola pombalina: (a) general floor plan [5]; (b) detail of half-timbered wall [6]

The types of connections and the dimensions of the cross sections of the elements varied, depending on the period in which they were built and the practice of the carpenter. In general, overlapped, dovetail, or simple contact connections were used between two elements, with the addition of nails to secure them in place [7]. Cross sections varied between 8 × 10 cm, 10 × 12 cm and 15 × 12 cm. Approximately a hundred years after their introduction, Pombalino buildings evolved to Gaioleiro ones, which lost the internal timber skeleton.

2. TESTS

2.1. Wall specimens and types of strengthening

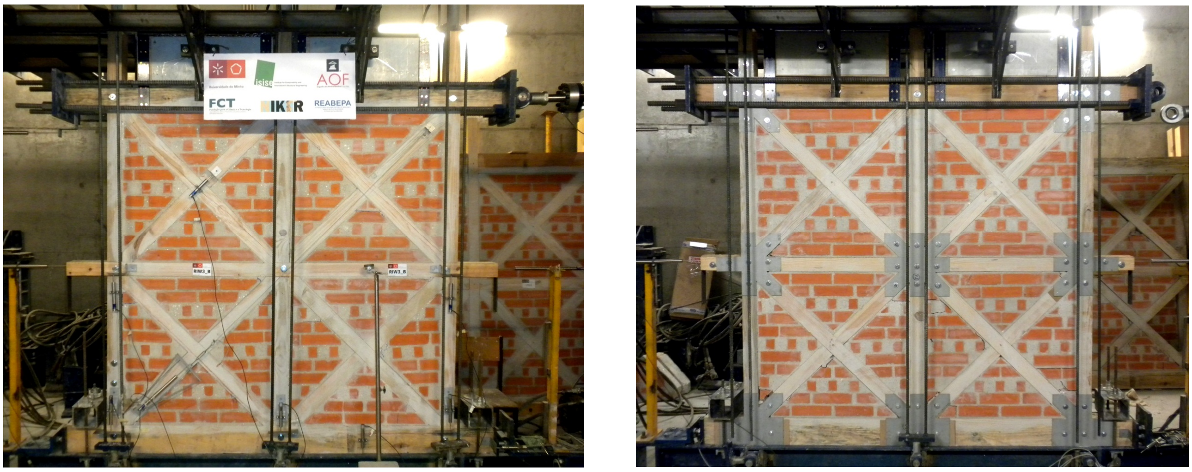
Half-timbered wall specimens were prepared according to dimensions found in existing buildings in Lisbon. All the connections between the vertical posts and the beams are overlapped ones, as well as the connections between the two diagonals of the St. Andrew's crosses, whilst the connections between the diagonal and the main frame are simple contact ones (see Fig. 2a).



(a) (b)

Fig. 2 Wall specimens: (a) connections used; (b) dimensions of elements in cm

The walls were built in real scale, with realistic cross sections for all the elements (see Fig. 2b). The walls were first tested in an unreinforced condition, and subsequently they were retrofitted and strengthened with two types of strengthening: 1) bolts were inserted in each of the overlapped connections between the main vertical posts and beams (Fig. 3a) and 2) steel plates were applied to all the main connections between the main posts and the beams on both sides, taking into account also the diagonal member attached, and they were secured with bolts (Fig. 3b).



(a) (b)

Fig. 3 Strengthening adopted: (a) bolts; (b) steel plates

2.2. Test setup and instrumentation

Cyclic tests were performed on half-timbered walls using a reaction wall to which a hydraulic actuator was attached, which applied the horizontal displacement to the walls (Fig. 4). The actuator was connected to the reaction wall and to the top beam through two-dimensional hinges that allowed vertical displacement and rotation of the top border of the wall. Three hydraulic jacks applied the constant vertical pre-compression on the posts and could follow the horizontal movement of the walls by means of rods attached to the top of the jacks and connected to hinges fixed at the bottom steel beam. The walls were restrained at the bottom using steel angles and plates that fixed the bottom beam of the walls to a steel beam which was connected to the reaction floor.

Out-of-plane movements were prevented by means of steel rollers attached to an external frame securing the top beam of the walls.

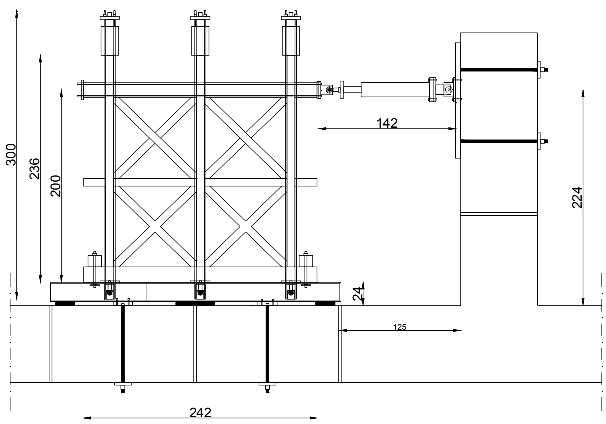


Fig. 4 Test setup used in the experimental campaign

Two different vertical loads were applied to the wall, namely 25 and 50 kN on each post. The application of different vertical load levels is significant, since the timber frame originally was not counted for the bearing of the vertical loads of the buildings, being their main function that of absorbing shear loads. But with modifications done to the structures, load redistributions could have occurred and additional loads could be present, which could be taken by the half-timbered walls.

2.3. Test procedure

A cyclic test procedure was adopted following standard ISO DIS 21581 [8], adding more steps in the procedure in order to better capture the highly non-linear behaviour of the walls. Due to limitations of the test equipment, the cycles were introduced with a sinusoidal law (Fig. 5), but no significant alterations were found in the tests when compared to others performed previously with linear cycles.

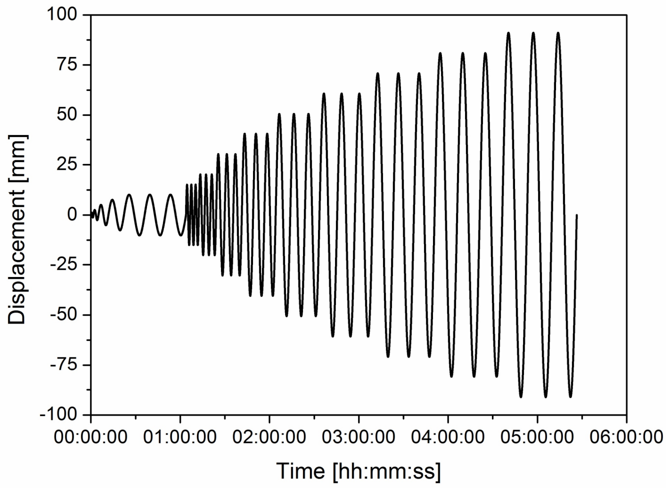


Fig. 5 Cyclic procedure adopted for the tests

Two different test speeds were adopted: for displacements up to 10% of the maximum one an average speed of 0,05mm/s was used; for higher displacements, a speed of 0,35 mm/s was adopted. The cyclic tests did not reach the ultimate displacement attained during the monotonic test (101,34 mm), but only 90% of this displacement, but it proved to be sufficient for the wall to fail under cyclic loading.

3. CYCLIC TESTS

Static cyclic tests can simulate in a simple way the seismic loading and provide important information on the overall mechanical behaviour and shear resistance of walls subjected to seismic actions. Cyclic test results performed on both unreinforced and strengthened walls are here presented and a discussion of their general behaviour is reported.

3.1. Results on unreinforced walls

Half-timbered walls were first tested in the unreinforced condition, subjecting them to an horizontal displacement proportional to the maximum horizontal displacement capacity of the wall achieved in a monotonic test, which resulted comparable to other results obtained performing similar tests [9].
A distinctively different behaviour can be noticed with a varying vertical pre-compression. The typical S-shape curve of a flexural response with a rocking mechanism at the bottom of the wall is evident for the walls subjected to a lower vertical load level (Fig. 6a), whilst a predominant shear behaviour is encountered in walls under a higher vertical load level (Fig. 6b).

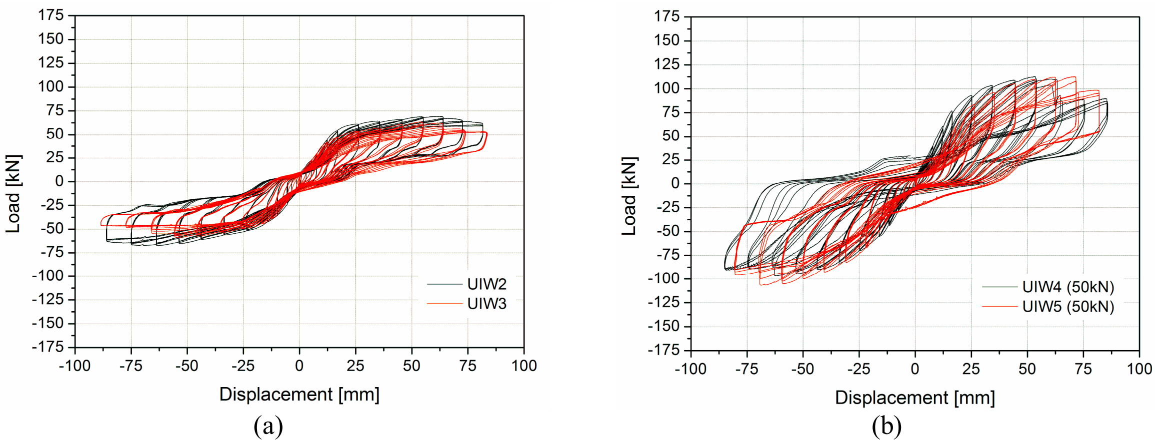
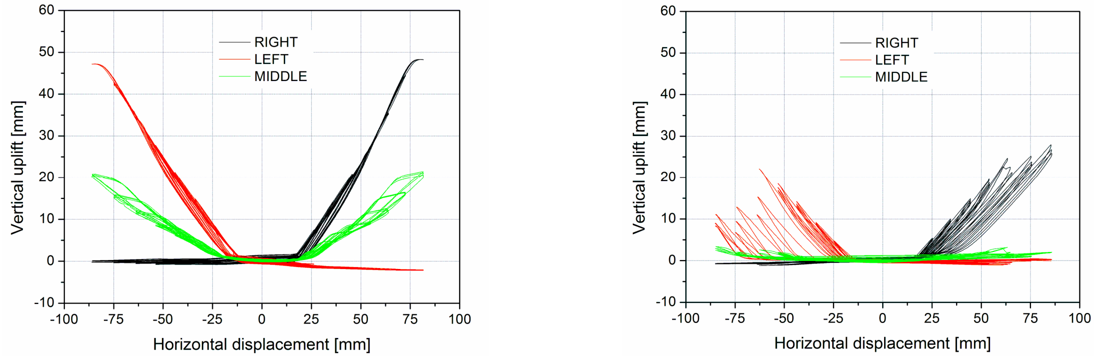


Fig. 6 Hysteretic curves for unreinforced walls: (a) lower vertical load level: (b) higher vertical load level

The walls exhibited, for low vertical load levels, a highly predominant flexural behaviour. They reach the maximum load level at a horizontal displacement of approximately 50mm and the subsequent loss of capacity is 20% of the maximum load or less. Due to the connection type, the vertical posts uplift during the test and the wall rocks back and forth. The lateral posts uplift as much as 50 mm (Fig. 7a).



(a) (b)

Fig. 7 Vertical uplift of posts for right, left and middle connection in unreinforced wall specimens: (a) lower vertical load level; (b) higher vertical load level

When a higher vertical pre-compression level is applied, the domineering mechanism is shear, but the flexural mechanism is still present, as it can be seen from the amount of vertical uplift of the lateral posts, which is lower (42%) if compared to the wall subjected to a lower vertical load, but it still characterizes the response of the wall. The walls tested under a higher vertical load level reach their maximum capacity at approximately the same horizontal displacement, but the post peak loss of capacity is higher (33% for UIW4 and 22% for UIW5). When observing the hysteretic curves of the walls (Fig. 6), the change in stiffness that can be observed in the unloading path occurs when the vertical uplift of the bottom connections returns to be zero, thus increasing the stiffness of the wall, as more resistance is given by the posts.
For the lower vertical load, the walls do not present significant damage, while it is present for the walls tested under the higher load. In fact, while the walls subjected to the lower level fail due to the opening of the bottom connections, with the vertical posts uplifting at the bottom (Fig. 8a), the higher loaded walls fail due to shear in the central connection (Fig. 8b) with wood crushing. The bottom connections tend to open and uplift in this case too, but they don't control the general wall failure.

(a) UIW3 (b) UIW5

Fig. 8 Uplifting of posts and opening of connections

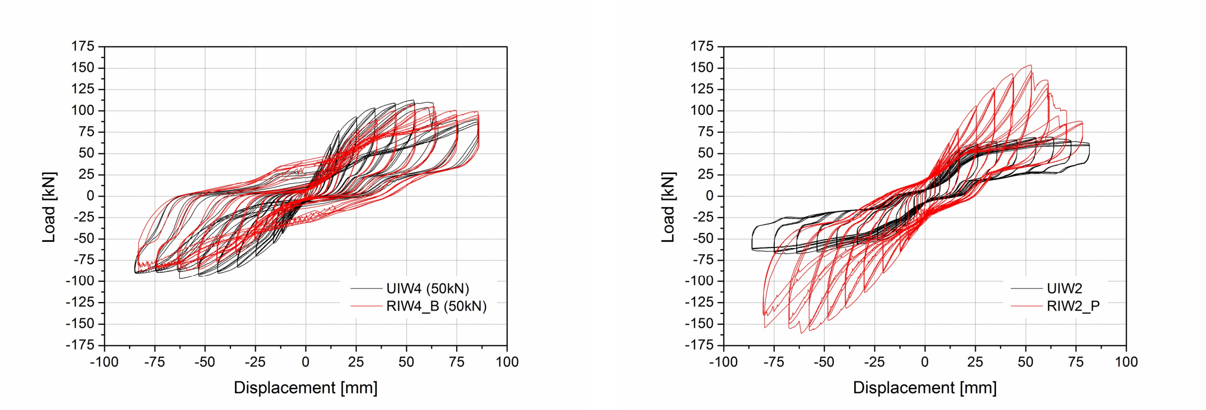
Concerning the infill behaviour, masonry behaved like a block. Few fissures could be observed, mainly mortar falling out at corners and corner bricks falling out due to nails tearing-off. A few compression cracks were visible. The blocks of masonry tended to move out-of-plane, as the adhesion of masonry to timber is very low and when the elements uplifted the masonry would detach and move out. After the test, it was almost always possible to push the masonry blocks back into place, so that masonry degradation did not influence the performance of the strengthened walls.

3.2. Results on strengthened walls

The tested walls were retrofitted, strengthened and tested again. As stated previously, the damage to masonry was recovered completely. The same cannot be said for the damage to the timber to timber connections. The nails tore the wood and, in the case of the walls subjected to the higher load, the vertical element of the central connection had to be substituted, introducing a new element to the post which was glued with a structural glue in order to guarantee the continuity of the element.

In the case of strengthening done with bolts, the improvement in terms of load capacity, energy dissipation and ductility is not overly significant. For the lower vertical load level, the retrofitted wall experienced a gain in terms of load capacity of 24%, while for the wall subjected to a higher vertical level there was no gain (Fig. 9a), but the wall regained its initial capacity and improved in terms of energy dissipation. The insertion of bolts did not influence the overall behaviour of the walls. The response of the wall is characterized by a combination of flexural and shear mechanisms, the posts continue to uplift, though the vertical uplift decreased of 40% when compared to the unreinforced condition (Fig. 10a). The main advantage is that the connections were now unable to open out-of-plane, thus allowing them to function until the ultimate displacement, whereas in the unreinforced specimen, the opening of the connection effectively caused that connection to cease working properly. For wall RIW4_B, the reduction of the vertical uplift (Fig. 10b) was less (30% when compared to UIW4).

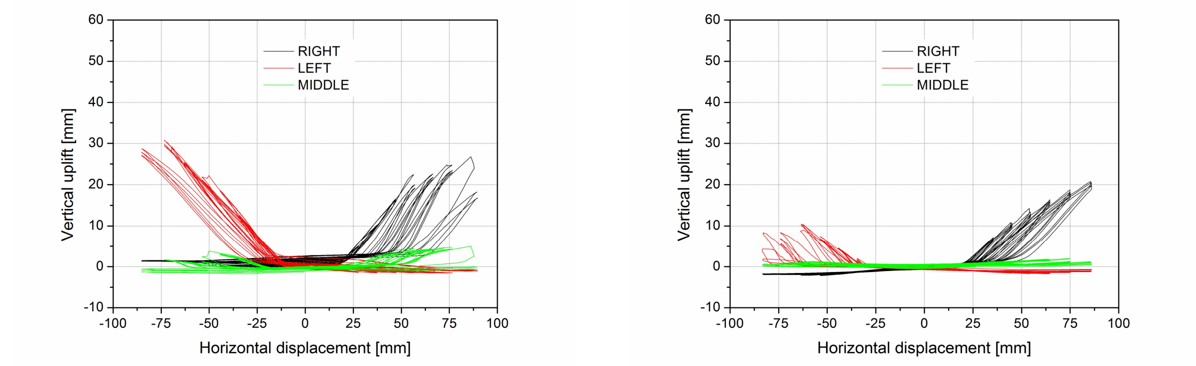
Thanks to the bolts, the connections worked properly and a shear failure was obtained even for the specimen subjected to a lower vertical load level, with the central beam tearing due to the shear caused by the diagonal elements.



(a) (b)

Fig. 9 Hysteresis curves of strengthened walls: (a) strengthening with bolts (higher vertical load level); (b) strengthening with plates (lower vertical load level)

For the wall specimen subjected to a higher vertical load level (RIW4_B), the failure occurred due to the crushing of the central connection caused by shear as well as the tearing off of the lateral central connection (Fig. 11a) which caused the wall to open in plane and reduced the stiffness of the wall in the unloading branch, since the left post was not participating fully to the reaction of the wall when the top beam was being pulled.

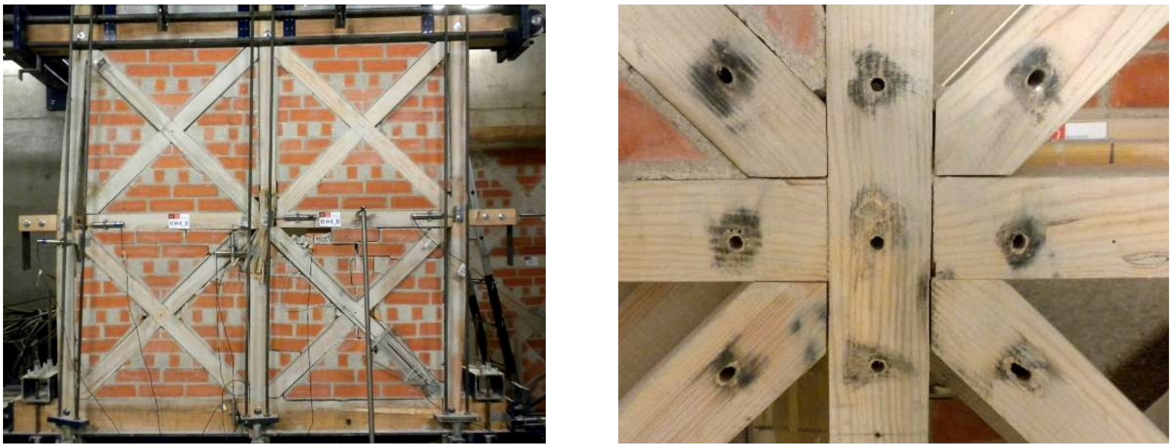


(a) (b)

Fig. 10 Vertical uplift of right, middle and left posts for walls strengthened with bolts: (a) lower vertical load level; (b) higher vertical load level

Analysing the behaviour of the walls strengthened with steel plates, it can be observed how this type of strengthening highly stiffens the wall (Fig. 9b). The gain in load capacity for the wall subjected to the lower vertical load level was of 121% when compared to the unreinforced condition. RIW2_P

failed due to failure of the bottom corner connection because the plate did not allow the post to uplift and the post tore in correspondence of the bolt.
The plates did not show great deformations, but the holes of the bolts generally deformed becoming oval, especially the ones corresponding to the diagonal elements of the central connection (Fig. 11b), which are the elements that work more as they push and pull the central connection, and those of the bottom connections, since those were the ones which normally tended to uplift more.
Wall RIW5_P showed a gain in terms of load capacity of 36% after an applied displacement of 50mm. The test was not completed due to problems in the equipment, but it was noticed that, even for the higher vertical load level, the strengthening with plates is highly efficient in terms of load capacity.



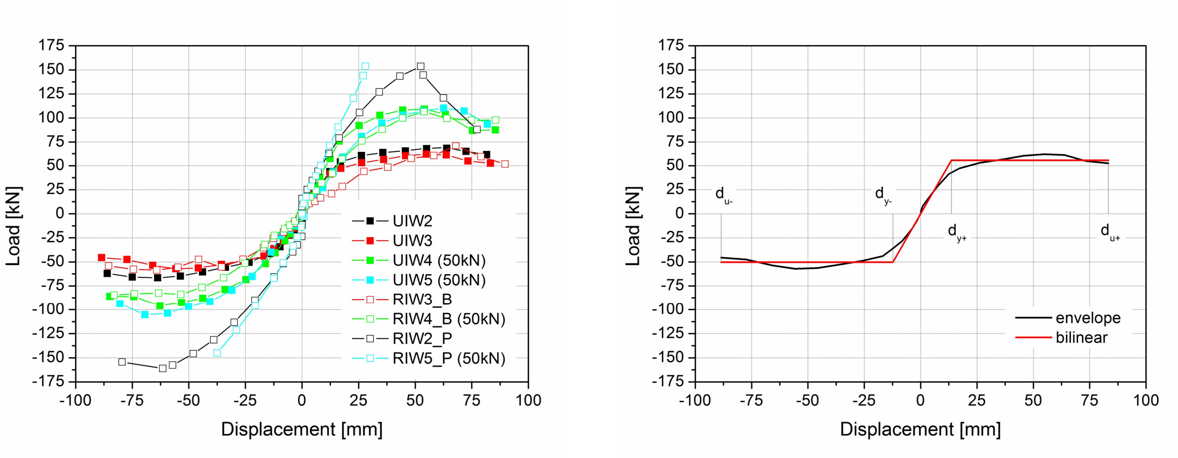
(a) (b)

Fig. 11 Typical damages in strengthened walls: (a) shear failure in RIW4_B; (b) holes in RIW2_P deformed becoming oval

4. SEISMIC PARAMETERS

The study of the seismic behaviour of a structure is essential when designing a new one or rehabilitating an existing one. Various parameters, such as ductility, energy dissipation, cyclic stiffness, equivalent viscous damping, characterize the behaviour of timber shear walls and can help in evaluating the performance of a structure under cyclic loading. Here, a few parameters are presented.
The envelope curves of the first cycle repetition of the hysteretic diagrams were obtained joining the points corresponding to the maximum load reached during each cycle at its respective displacement [8]. Fig. 12a shows the curves obtained in such a manner. From the envelope curves, the initial stiffness of the walls was obtained, considering the portion of the curve up to 40% of the maximum load to calculate the secant stiffness, as stated in [8]. Among the unreinforced walls, the vertical pre-compression level did not influence significantly the initial stiffness. All walls exhibited a similar stiffness, values varied between 4 and 4.5 kNmm, except for wall UIW5, which had an initial stiffness of 3kNmm, lower than the others because it experienced pinching from the early stages, due to important clearances in the connections. For the strengthened walls, strengthening done with bolts did not increase the initial stiffness, the walls were retrofitted but the connections had already suffered some damage from the tearing-off of the nails and the bolts could not recover the initial performance of the wall. In fact, for both vertical load levels, the initial stiffness decreased of almost 40% (the stiffness values were 1.89 and 2.59 kNmm for the lower and higher load level). For the plates strengthening, the walls showed an increase in initial stiffness of 50% (initial stiffness reached 6kNmm for both walls), pointing out how this method highly stiffens the wall, thus the significant gain in ultimate load, but reduces ductility, which from a seismic point of view is often more important than stiffness. Moreover, the initial stiffness of the two walls is very similar, possibly pointing out that for this type of strengthening, the vertical pre-compression level is not as significant as for the strengthening with bolts.
From an envelope curve it is possible to obtain a bilinear idealization of the same (Fig. 12b). Different methods can be used to obtain this idealization, for example the ones suggested in [10] or [11]; in this study the approach proposed by Tomazevic was used [11], i.e. the failure load was considered as 80% or more of the maximum one and the yield displacement and load were calculated from the equivalence of the areas underneath the curves considering the initial stiffness obtained from the

envelope curves. From here the values of ductility were derived for the various walls tested. In general, the unreinforced walls presented a higher ductility and among these, the walls with a lower vertical pre-compression level had the highest ductility (an average ductility of 6.5 versus a ductility of 3.5 for the walls with higher load). Among the strengthened walls, the strengthening carried out with bolts did not improve the initial stiffness of the walls or their ductility. Nonetheless, the walls were able to perform well and reached the same load capacity of the original walls. The bolts strengthening appears to give a better performance in the post-peak, since it keeps the connections closed so that they can continue to work, which did not occur in the unreinforced situation. The plates strengthening gave similar results to the bolts one in terms of ductility; all strengthened walls had a ductility of 3.0.



(a) (b)

Fig. 12 (a) Envelope curves of tested walls; (b) example of bilinear idealization of envelope curve

The energy dissipated by the walls is computed at each load cycle by calculating the area enclosed by the loop in the load-displacement diagram. It represents the amount of energy dissipated during the cyclic loading which occurs through friction between joints, yielding of nails and non-recoverable deformation (residual deformation) in the wall panel.

The low values of dissipated energy (Fig. 13) for low levels of vertical pre-compression are associated to the predominant flexural rocking mechanism prevailing for this load level. Walls subjected to a higher vertical pre-compression (UIW4 and UIW5) present higher dissipated energy.

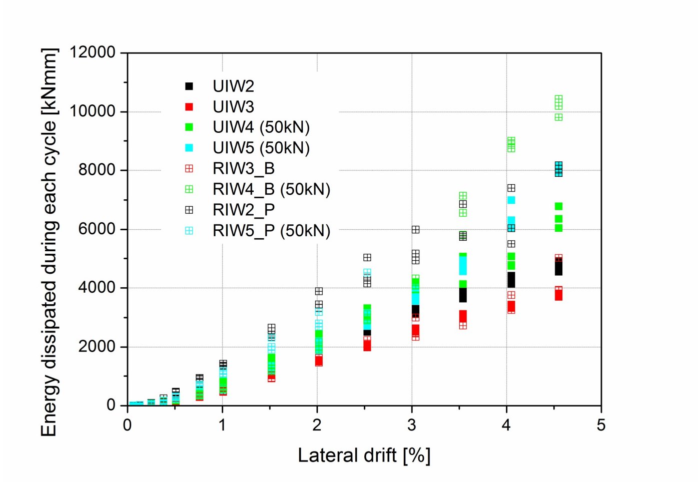


Fig. 13 Energy dissipated during each cycle vs. lateral drift of the walls

There isn’t a significant improvement in terms of energy dissipation between the unreinforced and the wall strengthened with bolts. Nonetheless, since the walls were already tested and the strengthening solution considered was extremely simple and did not change much the original behaviour of the wall, it can be pointed out how with these few devices the walls were restored to their original conditions and improved their performance for higher values of drift. In the case of the walls strengthened with plates, for the lower vertical load level, which is the only case that has complete data, the gain in terms of dissipated energy is evident from low values of lateral drift, pointing out how the steel plates represent a more efficient strengthening even in terms of dissipated energy.

5. CONCLUSIONS

Static cyclic tests were performed on traditional half-timbered walls. The behaviour of unreinforced walls and retrofitted and strengthened walls was compared in order to understand their behaviour in seismic situations. In the unreinforced condition, a higher vertical load level led to a higher load capacity and energy dissipation. Damages to the timber frame were more important for higher vertical loads, whilst for the lower ones the damages concerned mainly some nails tear-off.

For the strengthened walls, bolts strengthening only managed to reinstate the walls to their initial condition, with some advantages in the post-peak behaviour in terms of resistance and energy dissipation. The plates strengthening proved to greatly stiffen the wall and increase considerably its load capacity, but ductility was compromised.

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