Assessment of the Seismic Behaviour of Unreinforced Traditional Half-timbered Walls

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SUMMARY:
Half-timbered buildings represent an important historical heritage in many countries. They are diffused in various regions for different reasons, among which for being able to resist seismic actions.
Despite the great popularity of this kind of structures, few studies are available on their global behaviour or on that of their single structural elements. The aim of this paper is to study the behaviour under cyclic loading of traditional half-timbered walls, with connections, materials and elements dimensions encountered in existing buildings.
Cyclic tests have been performed in order to evaluate the performance of distinct traditional retrofitting techniques of the connections, namely: (1) increasing the number of nails at the connection; (2) use of steel bolts; (3) use of steel plates. The idea is to compare the performance in terms of hysteresis loops and the assessment of the improvements of the cyclic response in terms of ductility and energy dissipation.

Keywords: half-timbered, cyclic tests, seismic behaviour, traditional connections

1 INTRODUCTION

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, low cost and the strength they offer and are used as well as a construction able to resist seismic actions. This latter issue is the research topic analysed here, as half-timbered buildings have been specifically designated as a seismic-resistant building in reconstruction plans in many countries, such as Portugal (Pombalino buildings), Italy (baraccata house), and Greece (in the island of Lefkada). All these buildings were characterized by an internal timber skeleton constituted of vertical and horizontal elements and braced with diagonal elements, the typical St. Andrew's crosses. This internal structure aimed at improving the global stability of masonry buildings, enhancing their capacity to dissipate energy under seismic loading. The origin of such structures probably goes back to the Roman Empire, as in archaeological sites half-timbered houses were found. These constructions later spread throughout Europe, but also in India, Turkey and in the Americas (USA, Canada, Peru). In each country different geometries were used, but the common idea is that the timber frame can resist to tension, contrary to masonry, thus providing a better resistance to horizontal loads and conferring a sort of confinement to the masonry structure (Langenbach 2009).

The aim of this paper is to present a preliminary study on the behaviour of half-timbered walls, characteristic of Pombalino buildings, considering different connections at the base of the walls that can be found in practice and to choose the best solution for an on going experimental campaign that will interest the study of the cyclic behaviour of unreinforced infill walls and the possible strengthening solutions of retrofitted half-timbered walls.

1.1 Seismic Performance Experience from Recent Earthquakes

In some recent earthquakes (Turkey 1999, Greece 2003, India 2005) the half-timbered buildings showed a better behaviour than unreinforced masonry buildings (Langenbach, 2007). In fact, this constructive system is pointed out by several authors as one of the most efficient earthquake resistant structure in the world (Langenbach, 2007; Cardoso et al., 2005; Makarios and Demosthenous, 2006). Its popularity is not only due to its seismic performance, but also to its low cost. Half-timbered structures combine the best features of masonry and timber, offering a better overall behaviour of the buildings under seismic actions.

However, even if practical evidences exist of their adequacy to resist to seismic action, the behaviour of half-timbered walls is not clearly understood and thus it is important to have a deep insight on their resisting mechanisms under lateral loading. In fact, this type of constructive system has not been taken into great consideration from the scientific research community but a great number of historical buildings are actually half-timbered, which means that the evaluation of its mechanical performance, particularly to seismic actions, can be valuable. Moreover, the great variability found in these buildings in terms of geometry, materials, modifications introduced in the structures make their seismic assessment a relevant research issue. With this respect, a possibility for the seismic assessment of half-timbered walls is the experimental analysis of these walls under static cyclic loads aiming at representing in a simplified way the seismic loading.

In recent earthquakes, such as the ones in 1999 (Kocaeli and Düzce) and 2003 (Bingöl), this type of construction demonstrated to be robust under seismic actions, being the major damage concentrated at the contemporary buildings. Approximately, 7% of the RC buildings collapsed as opposed to 0,5% of the traditional structures in the Gölcük district (Gülhan and Güney 2000). In the Ozanlar district, 28% of the RC buildings were heavily damaged or collapsed, 62% were moderately damaged against 24% of the half-timbered buildings (Gülhan and Güney 2000). An alternative to masonry infill can be found in *bagdadi* constructions, where short rough pieces of timber are used as infill material. This led to light weight, seismic resistant, economical structures, but were more disposed to decay (Gülkan and Langenbach 2004).

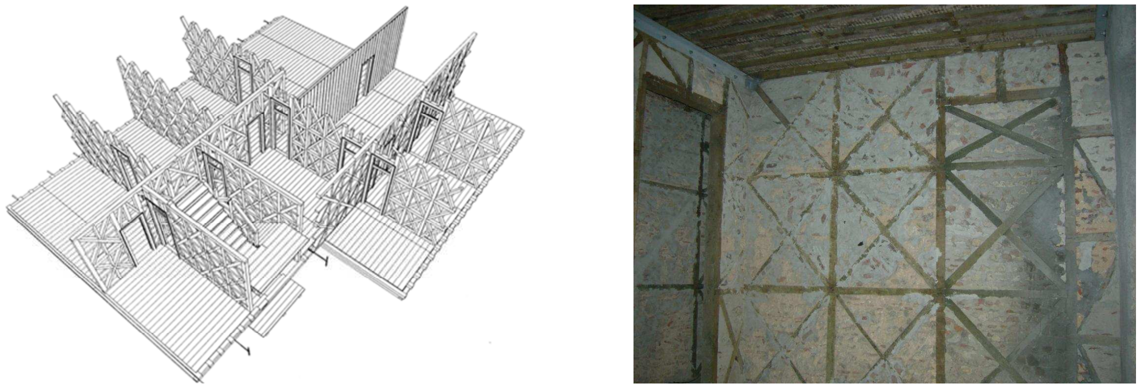
In the 2003 earthquake that interested the island of Lefkada, Greece, some RC buildings collapsed, whilst none of the traditional half-timbered buildings present on the island collapsed and damages were less relevant than those observed in modern buildings (Makarios and Demosthenous, 2006). Damages to the infill walls mainly interested the infill and the interfaces between infill and timber.

A good behaviour of half-timbered buildings was recorded even during the 2005 Kashmir earthquake in India (Langenbach 2009), during which earthquake some damages occurred to buildings were the original structure was modified or maintenance was poor.

1.2 The Portuguese Example – half-timbered Pombalino walls

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 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 (Figure 1a).

The gaiola was linked to the external masonry walls through the timber floor beams, to which it was connected. A lot of variations are met in the connections used here because construction technique varied based on the carpenter and during the years construction became less rule abiding. 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 (Figure 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)

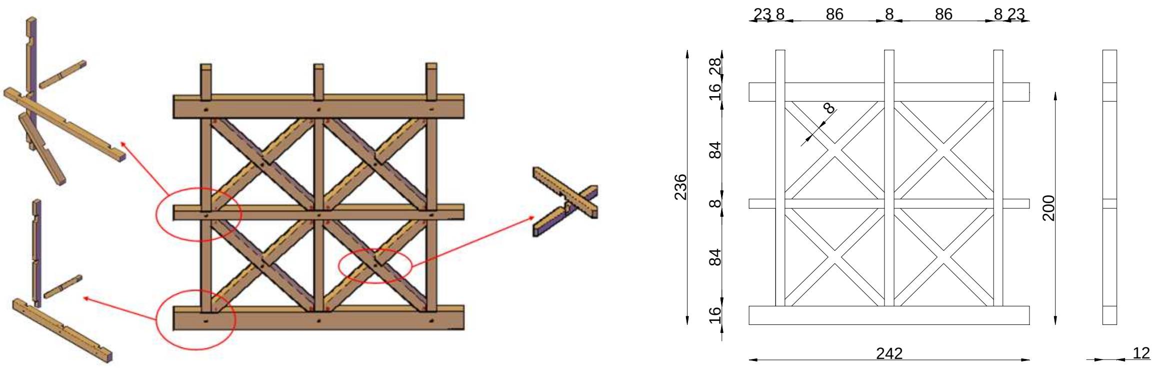
Figure 1. Examples of gaiola pombalina: (a) general floor plan (Coias 2007); (b) detail of half-timbered wall (http://eventos.fct.unl.pt/cirea2012/ 2012)

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 (Mascarenhas 2004). Cross sections varied between 8×10cm, 10×12cm and 15×12cm. Approximately a hundred years after their introduction, Pombalino buildings evolved to Gaioleiro ones, which lost the internal timber skeleton.

2 EXPERIMENTAL CAMPAIGN ON HALF-TIMBERED WALLS

Aiming at getting a detailed insight on the cyclic behaviour of Portuguese half-timbered walls, an experimental campaign has been designed on masonry filled and unfilled half-timbered walls under static cyclic tests. In fact, only reduced experimental results are available in literature (Vasconcelos et al. 2012, Meireles and Bento, 2010). Here, preliminary results are presented on walls aiming at validating the test setup.

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 Figure 2a).



(a) (b)

Figure 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 Figure 2b). A factor that influences the behaviour of the walls is the connection between the vertical posts and the bottom beam. A variability is met in existing buildings: (1) the post could be considered continuous between one storey and the next, connecting two timber elements with appropriate connections (for example a scarf joint); (2) they could be discontinuous and independent between two contiguous storeys; (3) at times, they could even be in different positions, connected to the base beam of the wall with half-overlapped connections. These variations led to a possible different behaviour of the wall, depending on how "strong" and fixed the base of the wall was. Thus, three configurations for the connections between the base beam and the posts were considered, namely: (1) overlapped connections with a single nail inserted; (2) overlapped connections with multiple nails inserted; (3) steel plates inserted in the connections with bolts and screws.

2.1 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 (Figure 3). 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 (25kN on each post) 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.

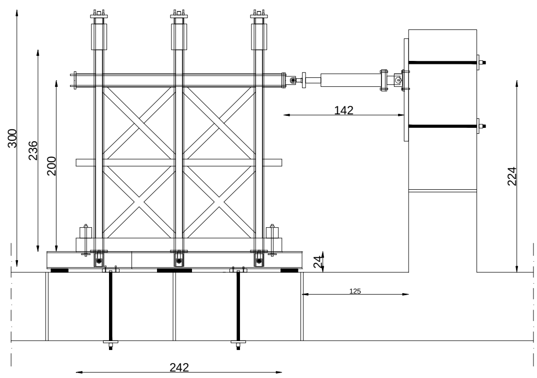


Figure 3. Test setup used in the experimental campaign (dimensions in cm)

Out-of-plane movements were prevented by means of steel rollers attached to an external frame securing the top beam of the walls. This system was necessary because, due to the asymmetry of the connections and the slenderness of the wall specimen, out-of-plane movements can occur for this structural element.

2.2 Test Procedure

A cyclic test procedure was adopted following standard ISO DIS 21581, 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 (Figure 4), but no significant alterations were found in the tests when compared to others performed previously with linear cycles.

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 0,35mm/s was adopted. The cyclic tests did not reach the ultimate displacement attained during the monotonic test (101,34mm), but only 90% of this displacement, but it proved to be sufficient for the wall to fail under cyclic loading.

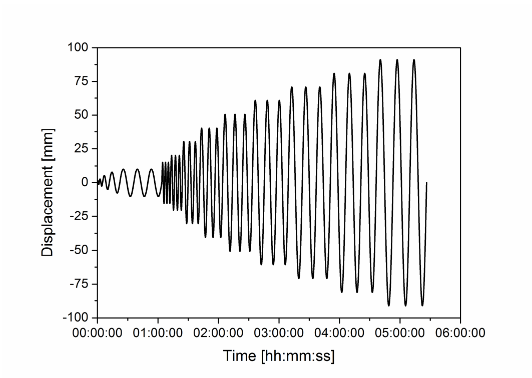


Figure 4. Time-displacement history imposed at the top of the walls

3 CYCLIC TEST ON UNREINFORCED HALF-TIMBERED WALL

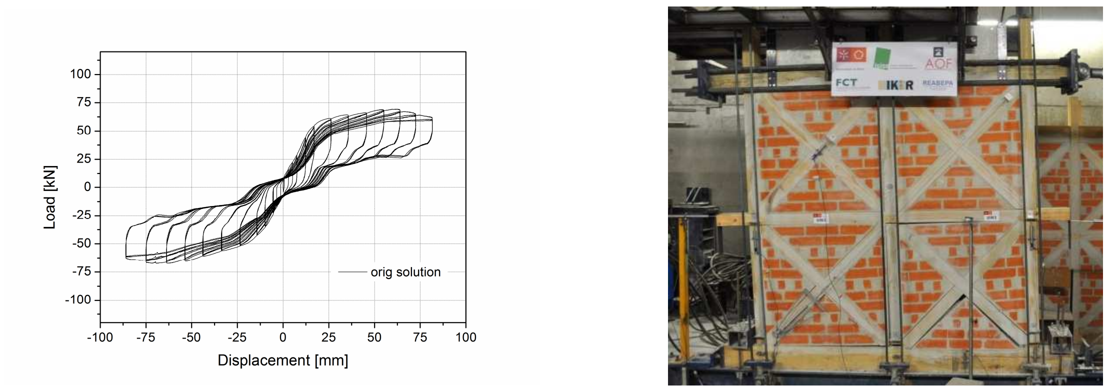
Static cyclic tests can simulate in a simple way the seismic loading and provide important information on the overall mechanical behaviour and shear resistance of walls subjected to seismic actions. Cyclic test results performed on half-timbered walls with different connections configurations at the base of the wall are here presented and a discussion of their general behaviour is reported.

3.1 Original Unreinforced Condition

As aforementioned, a cyclic test was performed on the wall in its original condition. As it is often found in existing timber frame walls and as planned initially, the first configuration represents the initial condition, where the bottom connections had only one nail, and the possible continuity of the post between two contiguous storeys was not considered.

The behaviour of the wall with this configuration for the bottom connections was characterized by a clear flexural resisting mechanism. This can be easily deduced from the typical S-shape of the hysteretic graph of the wall shown in Figure 5a. The hysteretic curves of each cycle are characterized in the descending branch by two easily distinctive “steps”, were the wall is reacting more to the displacement applied. These “steps” occur because the posts have a tendency to uplift, first the lateral one and then the central one, and when in unloading the wall the connections close, i.e. the posts lower, the change in stiffness in the unloading branch occurs. The lateral posts uplift as much as 50mm and the central one reaches an uplift of 22mm.

The wall fails when the bottom connections are not able to work anymore when they are pulled and the detachment of the posts from the bottom beam is complete.



(a) (b)

Figure 5. Wall with original bottom beam/ post connections: (a) hysteretic curves; (b) flexural behaviour of the wall during the test.

The rocking behaviour of the wall is evident from the deformed shape of the wall (Figure 5b). The whole wall has a tendency to rotate around a rotation point at the bottom corner of the wall, as it typically happens also in masonry walls with a flexural behaviour.

3.2 Additional Nails

To better understand the influence of the level of continuity in the bottom connections, additional nails were added to the three bottom connections, inserting the nails not only perpendicularly to the cross section, but also transversally (Figure 6a), in order to oppose more resistance to the out-of-plane opening of the connections. The total number of nails in each bottom connection was now 6 nails. Traditionally, a total number of two or three nails could be found in each connection, but considering that the nails used in this study were smaller, a greater number was used. The idea was to avoid the considerable high uplift of the vertical posts.

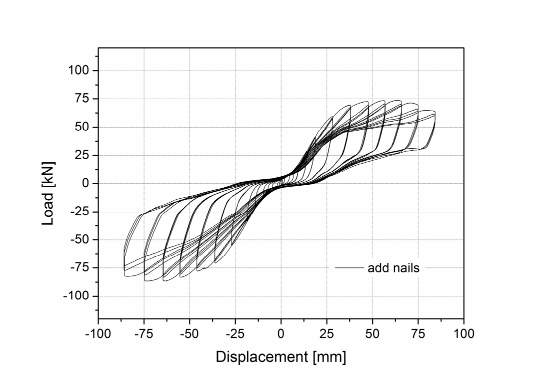
(a)

(b)

Figure 6. Additional nails inserted at bottom connections

For this test, nail pull-out was significant and pinching was much more evident than in the previous test. All the nails had the tendency to pull-out (Figure 6b) and the hysteretic loops (Figure 7a) are very flat for low forces, a behaviour which is associated with pinching, i.e. the behaviour associated to the nails which, tearing off the timber, create a free path that gives almost no resistance to the nail.

In this case, failure also occurs when the bottom connections do not work anymore, with the nails not being able to secure the connection.



(a)

(b)

Figure 7. Wall with additional nails at the bottom connections: (a) hysteretic behaviour of the wall; (b) deformation of the wall during testing

The wall was able to reach slightly higher loads when compared with the original solution, with an increase in maximum load of 7%. The behaviour of the wall is still flexural. In fact, the posts are still uplifting, even though with at a lower grade, with a maximum uplift of 36mm, corresponding to a decrease of 30% if compared to the original solution.

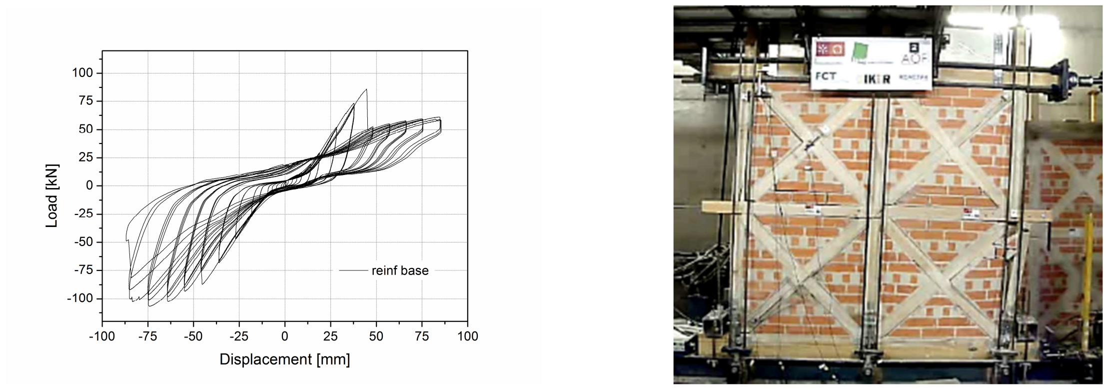
3.3 Reinforced bottom connections with steel plates

In order to try to reduce clearly the uplift of the posts and obtain a shear behaviour as pure as possible, commercial steel plates were inserted at the bottom connection on both sides of the wall. Since the overlapped connections have 3 shear planes, it was chosen to modify the commercial plates inserting, apart from the screws connecting the steel plate to the timber elements, a bolt that ties together the connection, avoiding the out-of-plane movements and helping against the uplift. In fact, using simple screws to secure the plates would not have prevented the uplift and the screws would have broken in shear.

(a) (b) (c)

Figure 8. Strengthening of base with steel plates: (a) front side vertical separation; (b) back side horizontal separation; (c) deformation of steel plate after test

The plates were able to secure the posts to the base of the wall, allowing a minimal uplift (5mm), since the steel of the plates allowed an elongation of 19% (Figure 8c). The hysteresis loops are still characterized by pinching (Figure 9a), but this time the behaviour is predominantly a shear behaviour.



(a) (b)

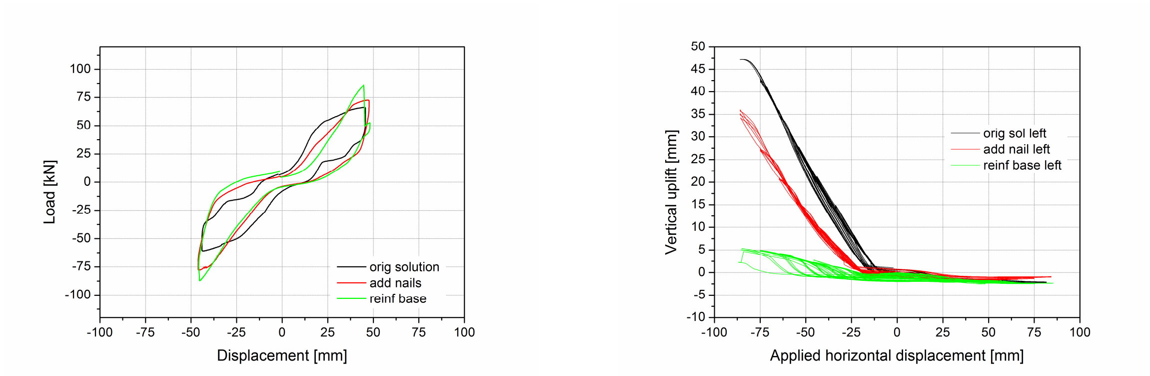
Figure 9. Wall with reinforced base: (a) hysteresis loops of the wall; (b) deformation of the wall during testing

The constraining of the bottom connections allowed the wall to gain in terms of ultimate load, which increased of 43% when compared to the original solution. The steel plates deformed in the linear range and the nails and bolts only experienced slight deformations, preventing the uplift of the posts. Moreover, with this solution, the connections at mid height were the ones more involved in resisting the shear stresses, so now the damages are concentrated at that height and the failure occurred at the lateral connection at mid height, in correspondence of the overlapped connection.

4 COMPARISON AMONG THE BEHAVIOURS AND ADOPTION OF A SOLUTION

In order to choose the best solution for the wall specimen to use in the experimental campaign that will study the cyclic behaviour of unreinforced half-timbered wall specimens and subsequently that of the same walls retrofitted, the behaviour of the walls with different posts-to-base beam connections was studied and compared.

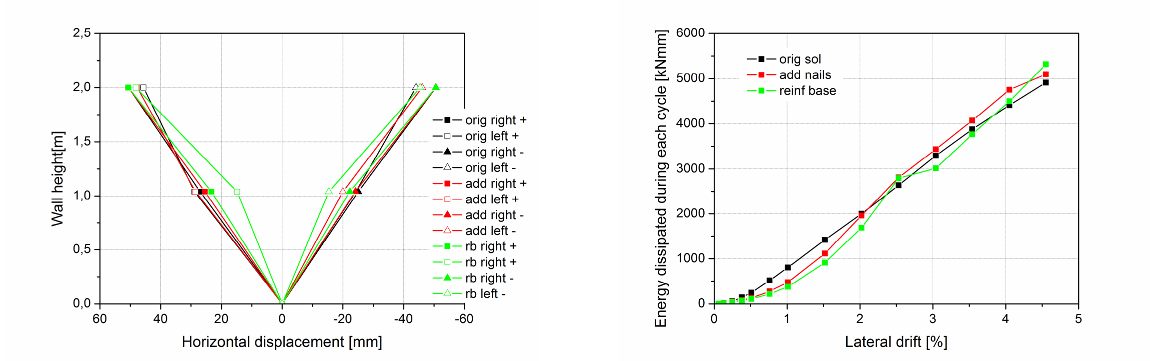
The different behaviour of the base connections can be understood analysing a typical hysteresis loop for each test. Figure 10a shows the hysteretic loop corresponding to an applied horizontal displacement of 50.61mm, which in all tests coincides with the cycle at which the maximum load was reached. It can be noticed how the loop of the original solution reaches a lower load, but has a comparable stiffness at that cycle as well as a similar dissipated energy, i.e. the energy enclosed in the loop. The solution with additional nails and the one with the steel plates reach a higher load and have a smoother unloading path, since the vertical uplift is lower than that of the original solution (Figure 10b), but the uplift begins for all solution at the same applied displacement. The wall specimens with a more efficient base connection present a higher level of pinching, which tends to reduce the dissipated energy.



(a) (b)

Figure 10. Wall behaviour with different bottom connections: (a) typical hysteresis loop; (b) vertical uplift of lateral bottom connection

The walls with only nails in the connections present a flexural behaviour. This can be deduced also by the deformation of the wall. Actually, if one considers the horizontal displacement of the wall at different heights (Figure 11a shows the progress at a given top displacement of 50mm), it can be seen how walls subjected to a flexural behaviour exhibit a linear trend of the horizontal displacement with the height of the wall, whilst the wall specimen with the reinforced base exhibits a non-linear progress of the lateral displacement, meaning that the wall is deforming in shear.



(a) (b)

Figure 11. Wall behaviour with different bottom connections: (a) lateral deformation of walls; (b) energy dissipated by walls during each cycle

Considering the energy dissipated by each wall during the cycles (Figure 11b), the original specimen has almost a linear trend, while the other two configurations have an exponential trend. In terms of values, there are no great differences, but they still point out some characteristics of the walls.

The solution with a reinforced base dissipated less energy for low values of drift, when the behaviour of the wall is still mainly linear for this wall, and then the dissipated energy tends to increase at a higher rate than that of the other solutions, until failure is reached in the wall, so that the energy drops slightly and then it starts increasing again as the wall regains some resistance.

For the wall with additional nails, the same trend is observed; the linear part interests higher values of lateral drift, so at the beginning the wall is dissipating less than the original solution, and then as the behaviour becomes non-linear. This configuration dissipates slightly more energy, since, even though the hysteretic curves have similar strength and stiffness, the loops for the wall with additional nails, for higher displacements, are larger and have a smoother descending branch, since the uplift is lower. Notice that the increase on the fixity degree of the bottom connections influences considerably the unloading branches of the hysteresis diagrams, which is associated to the decrease of the uplift of the post from the bottom beam and to a more reduced detachment of the connection.

In terms of ductility, which can be obtained from the bilinear idealization of the envelope curves of the walls (Figure 12), ductility is higher for the original solution (5.88), while for the wall with additional nails the value of ductility was of 3.13 and for the one with the reinforced base was 2.20. These changes happened because the wall with the original solution presents a higher initial stiffness and lower loads.

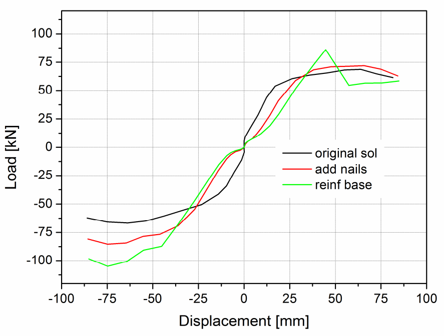


Figure 12. Envelope curves of three proposed solutions

Considering the overall behaviour of the walls and the traditional connections found in existing buildings, and considering that the walls tested will be then retrofitted and strengthened, the choice made was to maintain the original solution of the unreinforced half-timbered wall with only one nail in each overlapped connection. The behaviour of the wall is a clear flexural one, while the walls should behave as shear walls, so their full seismic capacity is not taken advantage of. But it has to be taken into consideration that the gain in terms of ultimate load and energy dissipation are significant only when compared to the results of the specimen with the steel plates inserted at the bottom connections, but this configuration could be considered already a strengthening solution, since various existing buildings present weak connections at the base of the floor, being the posts discontinuous. So in this study, it was chosen to admit the flexural behaviour of the half-timbered walls and to try to improve their performance in the strengthened solution. But it has to be pointed out how, just by changing the connections of one level of the wall greatly alters its overall behaviour and grants a more active participation of the wall in the shear absorption of the structure.

It also has to be pointed out that for all three configurations the masonry experienced little damaged, with separation in the interface between timber and masonry and with cracks at the corners, where the masonry was falling out due to the pulling out of the nails in the diagonals.

5 CONCLUSIONS

The cyclic behaviour of traditional half-timbered walls was studied in terms of the influence of the connections on the global behaviour of the wall. Traditional connections in existing half-timbered buildings presented great variations, so the choice of the best connection representing reality is not an easy one. The base connections chosen were the traditional overlapped connection and two alterations: one adding more nails and one adding steel plates and bolts to fix the posts to the bottom beam. The difference in the behaviour regarded mainly the vertical uplift of the posts and the behaviour which went from flexural to shear. The solution with additional nails did not significantly alter the behaviour of the wall, whereas the steel plates granted greater ultimate load and energy dissipation, but lower values of ductility. Moreover, considering that the walls will be subsequently retrofitted, the solution with still plates was disregarded, as it could be already considered a strengthening solution, since not in all the existing buildings the studied connections could be considered fixed. The main result is the understanding of how the connections of half-timbered walls at the bottom level control the overall behaviour of the structure and should be the focal point in every study concerning half-timbered walls.

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