

INFLUENCE OF INFILL ON THE CYCLIC BEHAVIOUR OF TRADITIONAL HALF-TIMBERED WALLS

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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, low cost and 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, India, Greece, etc.

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. Traditionally, different types of infill could be applied to half-timbered walls depending on the country, namely brick masonry, rubble masonry, hay, mud, etc. The focus of this paper is to study and compare the seismic behaviour of the walls considering two different infill typologies, as well as the possibility of having no infill, i.e. considering only the timber frame. Cyclic test were performed on traditional walls and their behaviour was studied in terms of ultimate capacity, deformability, energy dissipation and stiffness.

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 and thus, a better understanding of their seismic behaviour is essential in order to be able to adequately intervene in a structure. But due to the great variability encountered in these structures, it is also important to analyse the influence these factors can have on their behaviour. Among the varying factors, one can consider: infill material, type of wood, dimensions and geometry, type of connection. The aim of this paper is to study the influence of the infill material. For this reason, the cyclic behaviour of half-timbered walls with two typical infill materials, namely brick masonry and timber strips with mortar infill (known as *fasquio* in Portugal) have been analysed, as well as the behaviour of walls without infill, i.e. considering only the timber frame.

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 (Langenbach, 2007). But timber was used in masonry walls even in previous cultures (Mycean culture, Bronze Age) (Tsakanika-Theohari, 2008).

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, and Istanbul), new regulations (Vintzileou *et al.*, 2007; Tampone, 1996; C3oias, 2007) 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 Downtown Lisbon 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 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.

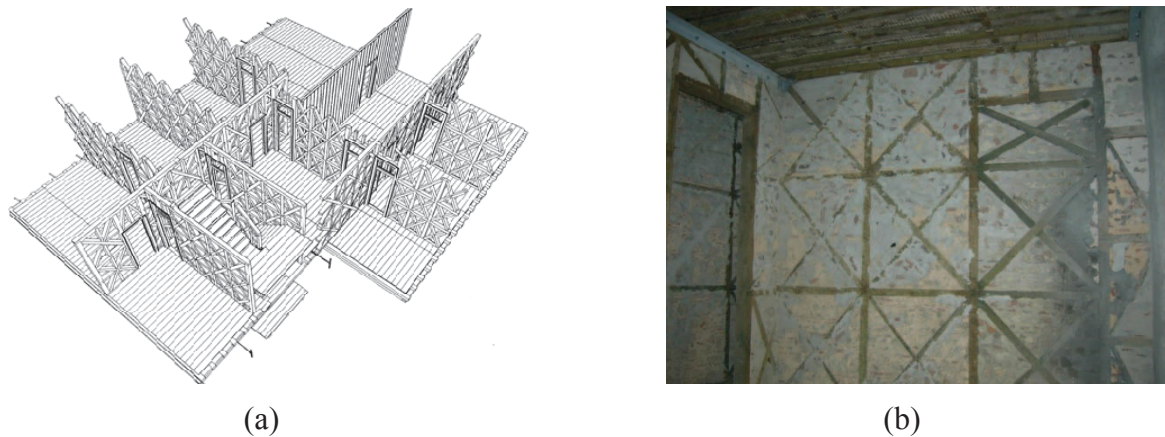


Figure 1: Examples of *gaiola pombalina*: (a) general floor plan (C3oias, 2007); (b) detail of half-timbered wall (<http://eventos.fct.unl.pt/cirea2012/>)

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, dove tail, 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 8×10 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.

As mentioned above, different types of infill could be used. In Portugal, rubble or brick masonry can be found, as well as “fasquio” infill, which consists of wood strips nailed to the wall with approximately 2cm spacing and filled with mortar. In Peru, a similar technique is used, in which bamboo canes are used instead, in the traditional “quincha”, where the spaces among the canes are filled with hay or mud. In India, both brick and rubble masonry can be encountered as infill with clay or mud mortar (“dhajji dewari” construction) (Langenbach 2009). In Turkey, similar construction typologies can be found: “himis” is a traditional timber frame structure with masonry infill, both rubble and brick, whereas “bagdadi” consists of the timber frame sheathed with timber boards.

2. EXPERIMENTAL CAMPAIGN PERFORMED ON HALF-TIMBERED WALLS

An encompassing experimental campaign has been carried out on the cyclic behaviour of half-timbered walls. The specimens tested are all in accordance to traditional half-timbered walls that can be encountered in Portugal.

2.1 Wall specimens and type of infill

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). The walls were built in real scale, with realistic cross sections for all the elements (see Figure 2b).

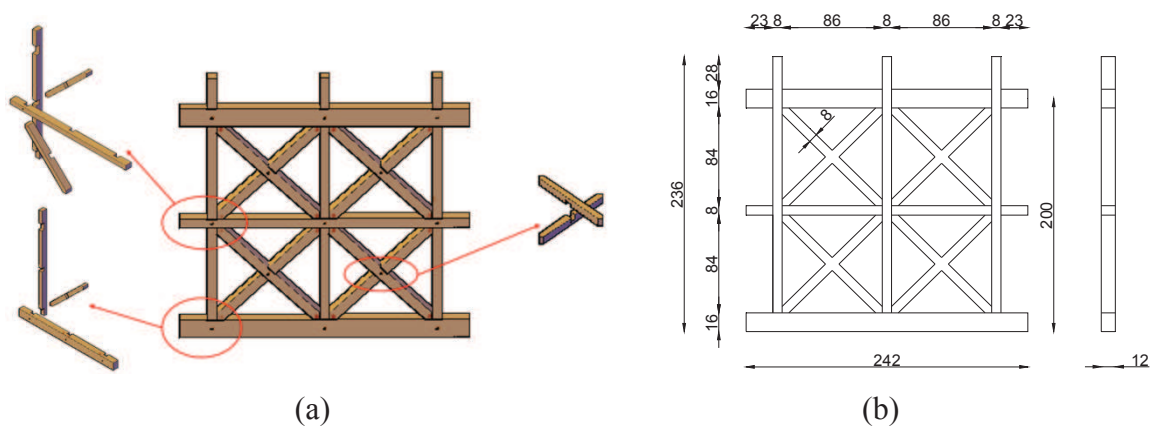


Figure 2: Wall specimens: (a) connections used; (b) dimensions of elements (in cm)

After the completion of the timber frame, part of the walls was filled to obtain the traditional half-timbered walls. It was chosen to use modern materials available in the market mainly to represent what it is done nowadays in the rehabilitation of buildings, since in order to have a lower cost of construction, modern materials are used. The bricks were cut in order to fit better into the triangular voids of the wall. This choice was made in order to avoid

having large portions of the masonry infill with only mortar due to the dimension of the brick. In fact, in historical buildings, bricks were usually smaller and moreover, rubble masonry could be used, thus having a more uniform distribution of the two components even in the corners. The masonry pattern chosen consists of double leaf masonry with transversal series of bricks every two rows of horizontal double leaf masonry (Figure 3).

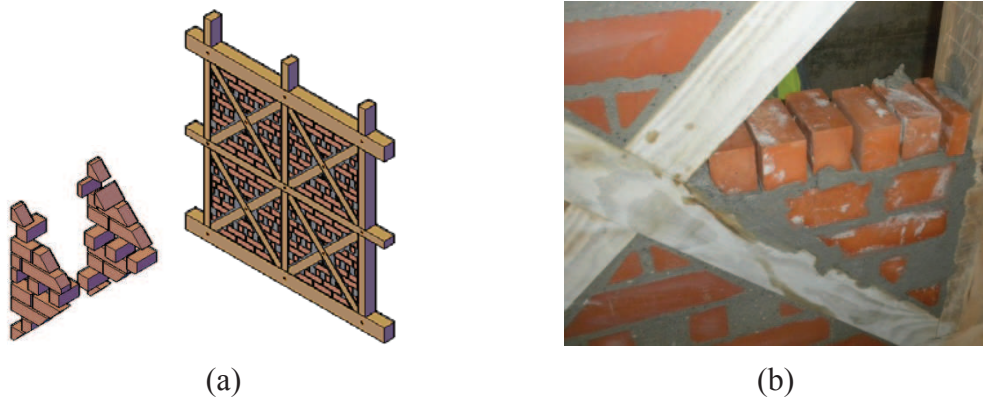


Figure 3: Half-timbered walls: (a) masonry pattern of infill walls; (b) detail of wall construction

The second kind of infill chosen for the walls consists of wood strips nailed with a nail gun to the timber frame. This kind of walls is known as fatchwork. The wood strips, which had a trapezoidal section (Figure 4) spaced of 2 cm, were not always continuous, but of varying length, and were nailed to each timber element they encountered with at least 3 nails.

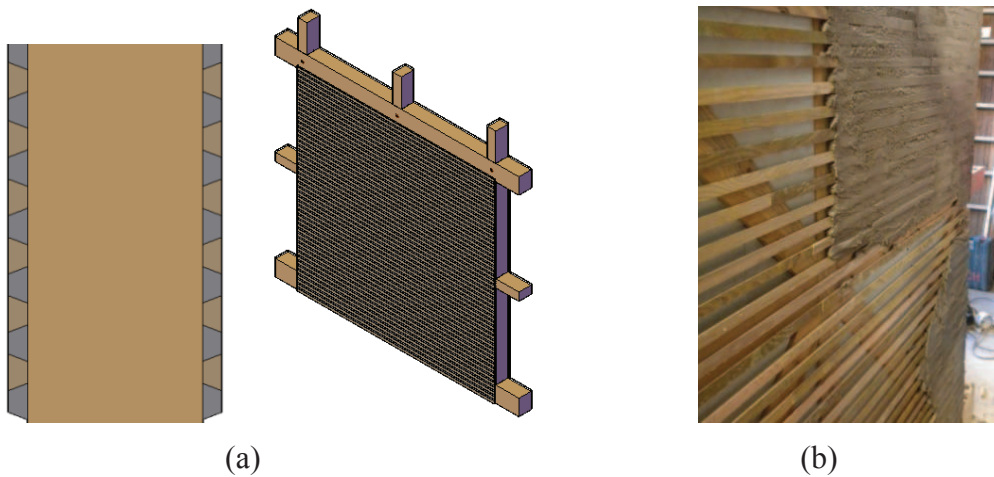


Figure 4: Fatchwork wall: (a) geometry of the wall; (b) detail of construction

Mortar was inserted between the strips (with the same ratio as that used for the masonry infill walls) and inside the timber frame for a thickness of 1.5 cm on each side of the wall. To prevent a higher mortar thickness, isolating panels were inserted in the wall to reduce the free space inside, but without providing any additional stiffness or weight to the wall.

2.2 Test setup, instrumentation and procedure

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 5a). 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.

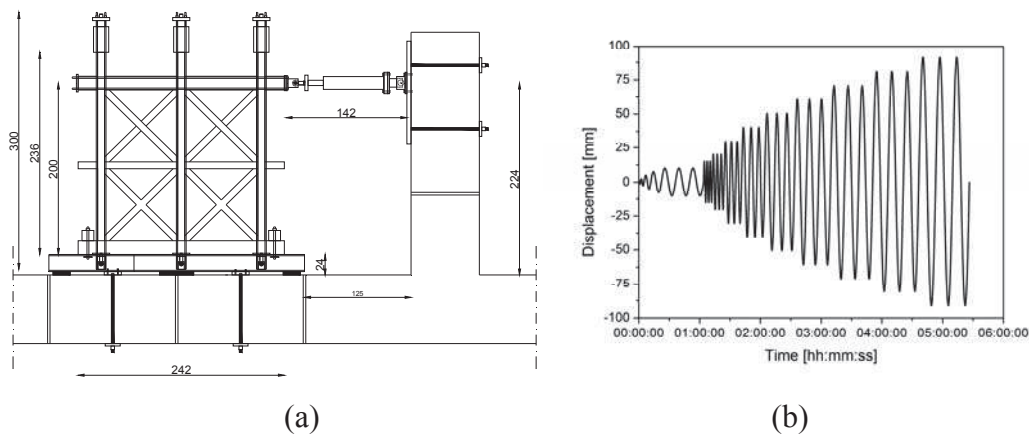


Figure 5: (a) Test setup used in the experimental campaign; (b) test procedure

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.

A cyclic test procedure was adopted following standard ISO DIS 21581 (2009), 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 5b), 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.

3. CYCLIC TESTS ON HALF-TIMBERED WALLS WITH DIFFERENT INFILL MATERIAL

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 infill and timber frame walls are here presented and a discussion of their general behaviour is reported.

All unreinforced half-timbered walls subjected to the lower vertical pre-compression level (UIW25) present a similar behaviour. The behaviour is highly non-linear since low values of displacement. The walls have a highly rocking behaviour, characterized by the S-shape of the curve (see Figure 6a), with a significant vertical uplift of the vertical posts (see Figure 6b). The lateral posts were uplifting as much as 50 mm, pointing out the important rotation experienced by the walls. This behaviour is due to the particular geometry of the wall, which presents in all connections overlapped connections. Since the bottom connections do not present the same continuity of the vertical element as the other connections in the post, the connection is a lot weaker, being simply a notched connection secured only by a nail, whereas in the other connections the continuity of the two timber elements prevents the early separation of the connection, which happens only if one element ruptures. Once the connections were completely open, the walls exhibited a low decrease in terms of strength. This behaviour is typical of the rocking mechanism, for which high displacements can be reached with little reduction of strength.

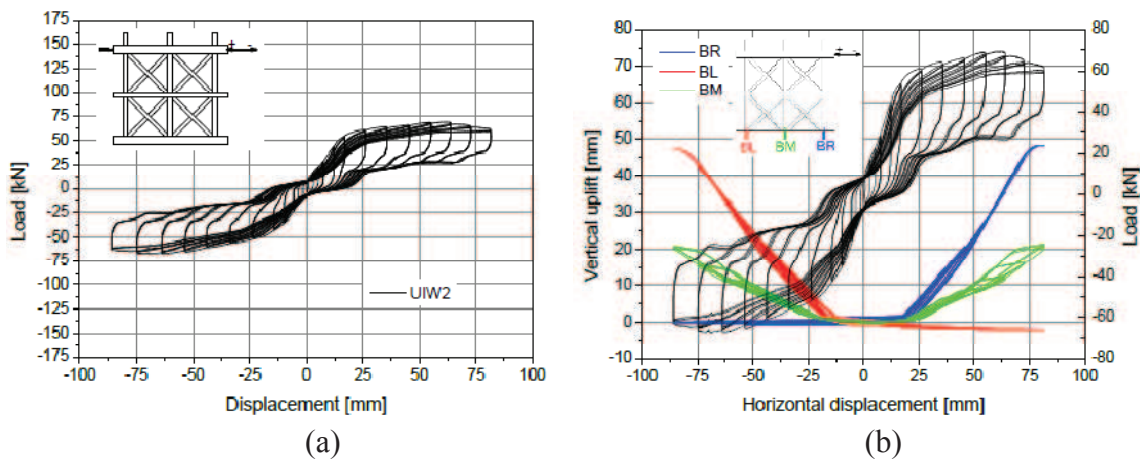


Figure 6: Hysteretic behaviour of half-timbered walls: (a) hysteretic loops; (b) vertical uplift corresponding to steps in loops.

The hysteretic loops present a peculiar form which is not present, for example, in similar tests conducted on modern timber walls (Lam *et al.*, 1997) or masonry walls (Vasconcelos and Lourenço, 2009). If we compare the form of the hysteretic loops with the uplift of the vertical posts for the same horizontal displacement, one can notice how first: the change in stiffness in the loading branch starts when the lateral posts start uplifting; second: the small steps in the unloading branch of each cycle occur when the bottom connections start closing.

In general, the walls were not greatly damaged. The only damages encountered consisted of the out-of-plane opening of the connections and low cracking in the masonry infill.

The walls tested under the higher vertical load level (UIW50) presented a noticeably different behaviour. The behaviour of the walls went from being flexural to being mainly a shear one (see Figure 7a), though a flexural component is still present. The walls exhibit a progressive loss of stiffness, even though the ultimate load does not differ greatly from the maximum one. The typical damage for this wall was the crushing of the central overlapped connections of the wall, which failed in shear. Pinching is still present, but it is not as noticeable as it was for the walls tested with the lower vertical pre-compression level.

The walls still exhibited uplift in the bottom connections, though significantly lower than that observed for the walls tested for the lower pre-compression. The posts uplifted up to 50% less than what observed in the previous tests. Still, the same shape of the unloading branch can be observed when the posts close, with a noticeable step. The typical shape of the walls in this case is more oval, having the behaviour of the walls a shear component which solicited more the posts in bending.

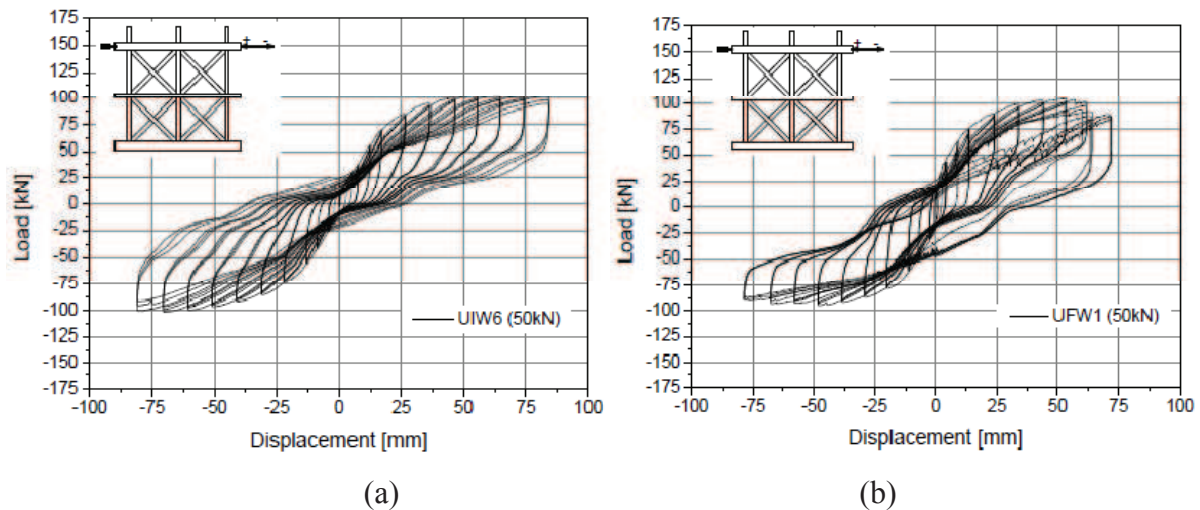


Figure 7: Hysteretic behaviour for higher vertical load level: (a) masonry infill; (b) fatchwork

The results on fatchwork walls for both vertical load levels were very similar to those observed for the masonry infill walls. The wall tested under the lower vertical load level (UFW25), exhibited a clear flexural behaviour, characterized by the S-shaped curve, while the wall tested with the higher vertical load level (UFW50) (Figure 7b), showed a dual flexural and shear behaviour, similarly to what observed for the walls tested with masonry infill.

The timber strips were able to grant stiffness to the wall, they were keeping the wall together, so the damages were once again concentrated in the posts, whilst no damages due to tensile stresses were observed in the central beam.

The behaviour was confirmed by the vertical uplift of the posts. The uplift was higher for wall UFW25, with a vertical uplift reaching up to 50 mm. Wall UFW50 reached a vertical uplift of 32.43 mm, still significant. In this case too, it is possible to notice the steps in the unloading branch of the hysteretic loop corresponding to the closing of the posts.

Damages to the walls were similar to what observed in the first type of infill, i.e. little damage for walls tested with the lower load, more significant damage for the walls tested with

the higher load, and concentrated in the central post in correspondence of the central connection.

Timber frame walls exhibited a different behaviour from that of the infill walls. The behaviour was a predominant shear one, again with a minor flexural component. But, as it can be noticed from the hysteretic curves (Figure 8a), the walls experienced severe pinching. Moreover, the unloading branch of the various loops is more regular, even if the “step” characterizing the post uplifting is still present. For the two vertical load levels, the vertical uplift of the posts was similar and minimal, if compared to that of the infill walls (13.8 mm for UTW25 and 17.51 mm for UTW50). Contrary to what happened in the infill walls, the uplift was higher for the wall tested with the higher vertical load level (UTW50), but this was due to the fact that the wall failed for higher levels of horizontal displacement and the posts were stressed more.

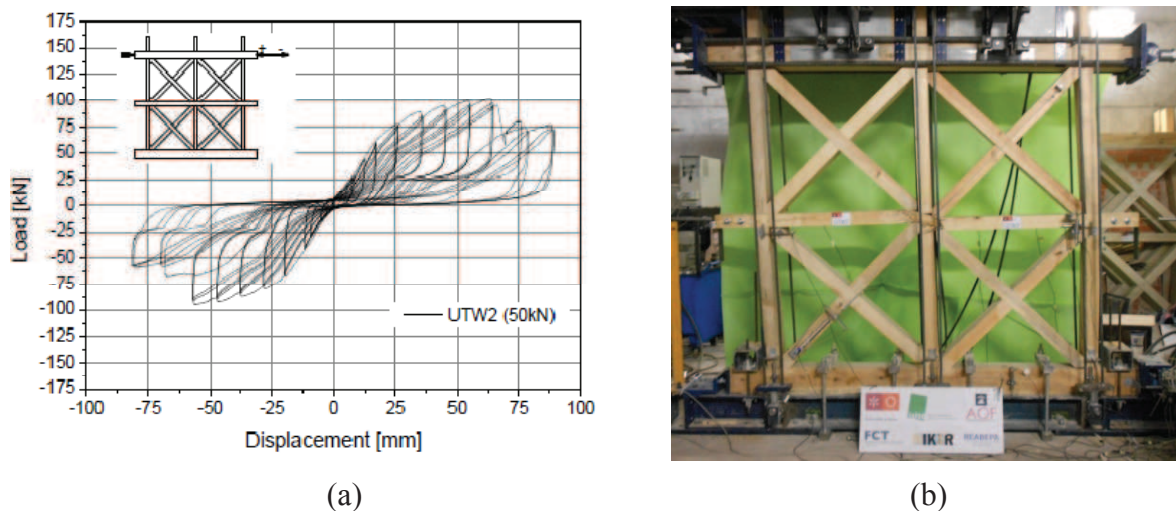


Figure 8: Behaviour of timber frame walls: (a) hysteretic behaviour for UTW50; (b) deformed shape of UTW50.

The timber frame walls encountered heavy damage for both vertical load levels. Contrary to what happened in the infill walls, the damages in the timber frame walls were concentrated in the central beam (Figure 8b), due to the higher shear behaviour of the wall which stresses more the beams in tension.

In terms of ultimate load, if for the walls tested with a higher load the maximum load value is comparable for the three walls typologies (c.o.v. 3.2%), for the lower vertical load level the timber frame walls did not reach the same load capacity (maximum load is 37% lower). Infill walls reached similar values of maximum load (c.o.v. 10%).

4. SEISMIC PARAMETERS

In the seismic design of new timber structures or in the rehabilitation of existing structures, including historic timber frame walls, the study of the seismic performance is of paramount importance. Since the seismic response of timber structures is very complex and time dependant, a better understating of the hysteretic factors that govern the problem is important for a safe and economical seismic design or for the adoption of the most adequate retrofitting

measures. Parameters such as ductility, energy dissipation, overall cyclic stiffness, equivalent viscous damping ratio and lateral drifts characterize the behaviour of timber shear walls and are helpful in evaluating the performance of a structure under cyclic loading.

The seismic parameters analysed confirm once more that the behaviour of infill walls is comparable, while the absence of infill changes the behaviour of the walls.

For example, in terms of ductility, for both vertical load levels timber walls exhibited lower values of ductility than infill walls. Timber walls had a ductility of 3.77 for the lower vertical load level, while infill walls reached values of 4.46. The same trend was noticeable for the higher load level, where the difference between the two values is even higher (35%).

In terms of cyclic stiffness (Figure 9), timber walls exhibit the lowest stiffness, but for higher values of drift the results of the three wall types are comparable, after 1.5% for the higher vertical load level and only after 3.5% for the lower vertical load level. UTW25 walls reached an almost constant value of cyclic stiffness after a value of drift of 1.85%, while walls UIW25 and UFW25 continued to lose stiffness for increasing values of drift. UTW50 instead, degraded its stiffness in a way more similar to what happened for the infill walls.

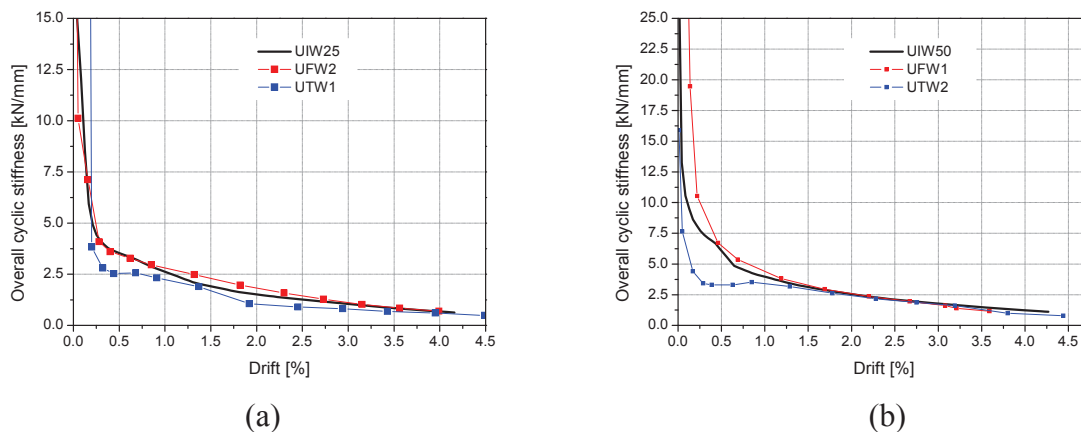


Figure 9: Overall cyclic stiffness: (a) lower vertical load level; (b) higher vertical load level

For values of drift less than 3.5%, stiffness was always higher for the walls tested with the higher vertical load. For drifts up to 2.5%, the cyclic stiffness was almost the double for the highly loaded walls. After this value, stiffness starts to be comparable for the two load levels.

A confirmation that infill helps in improving the seismic characteristics of the walls comes from the comparison of the trends in terms of energy dissipation (Figure 10). For both load cases, infill walls were able to dissipate a higher amount of energy for the same drift value. It should also be pointed out, that for the same amount of lateral drift, the energy dissipated by the walls tested with the higher vertical load level is almost the double of that dissipated by the walls tested with the lower load.

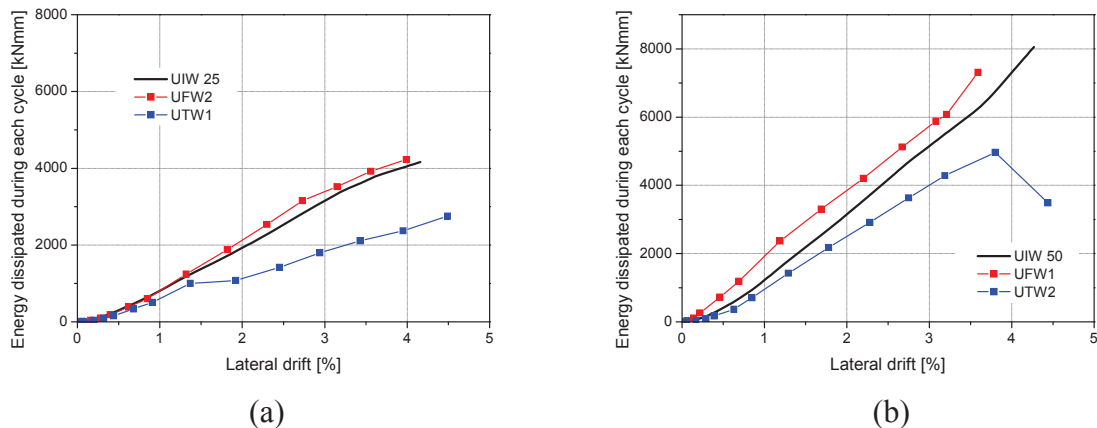


Figure 10: Dissipated energy: (a) lower vertical load level; (b) higher vertical load level

It is clearly deductible that the amount of vertical load directly influences the cyclic response of the walls, in particular in terms of lateral stiffness, load capacity and energy dissipation capacity. A higher vertical load leads to higher values for all this parameters. These observations are in accordance to what found by other authors as well (Johnston *et al.*, 2006; Dean and Shenton III, 2005).

5. CONCLUSIONS

- The presence of infill in timber frame walls clearly influences the cyclic behaviour of such walls.
- The presence of infill increases the cyclic stiffness of the walls, as well as their energy dissipation capacity and their ductility. The failure modes are influenced too.
- It appears that, for the two traditional infill chosen, the type of infill does not significantly changes the overall behaviour of the wall, as long as it is able to sufficiently stiffen the structure.
- Another parameter that clearly influences the cyclic behaviour is the amount of vertical load. A higher vertical load increases the stiffness as well as the load and energy dissipation capacity of the wall.

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