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An overview on the seismic behaviour of timber frame structures

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Introduction

Masonry and timber are materials used since ancient times in construction. Masonry buildings constitute an important percentage of the existing buildings and actions for their preservation should be taken, since a large part of historical buildings are actually in masonry. A drawback on the use of unreinforced masonry is the low resistance to tensile stresses, leading often to an inadequate behaviour under seismic actions. A historical construction solution to improve the mechanical behaviour of ancient masonry adopted in different locations at different times, namely in seismic regions, has been the reinforcement of masonry with timber.

Traditional timber frame walls are an important structural element of many buildings and are usually composed of vertical posts and horizontal beams with bracing diagonal elements. In Portugal the timber frame walls, known as *frontal* walls, are usually part of Pombalino buildings, which were introduced by the Marquis of Pombal, who was responsible for the reconstruction of Downtown Lisbon after the great earthquake of 1755, which partially destroyed the city. The timber-framed walls are connected to the external masonry walls by means of the timber floor beams, which are connected both to the timber-framed and to the external masonry walls [1]. This system can be also beneficial to reduce the out-of-plane vulnerability of the masonry walls. The timber frame walls are also identified in several countries particularly in local vernacular architecture, due to the low cost of such structures composed of timber and several infill materials since brick and stone masonry to mud and cane.

Given the increasing interest of the research community to this structural system, it is important to promote the discussion of the main findings that can contribute to the advance on the knowledge of the mechanical behaviour of timber frame buildings to seismic action.

Therefore, this paper intends: (1) to give an overview of the different solution of timber frame structures in different countries with special focus on the frontal walls characteristic of Pombalino buildings; (2) provide some examples of the reasonable behaviour of timber frame buildings in past earthquakes; (3) to summarize the experimental research carried out in the recent years in analysis of the behaviour to in-plane cyclic loading.

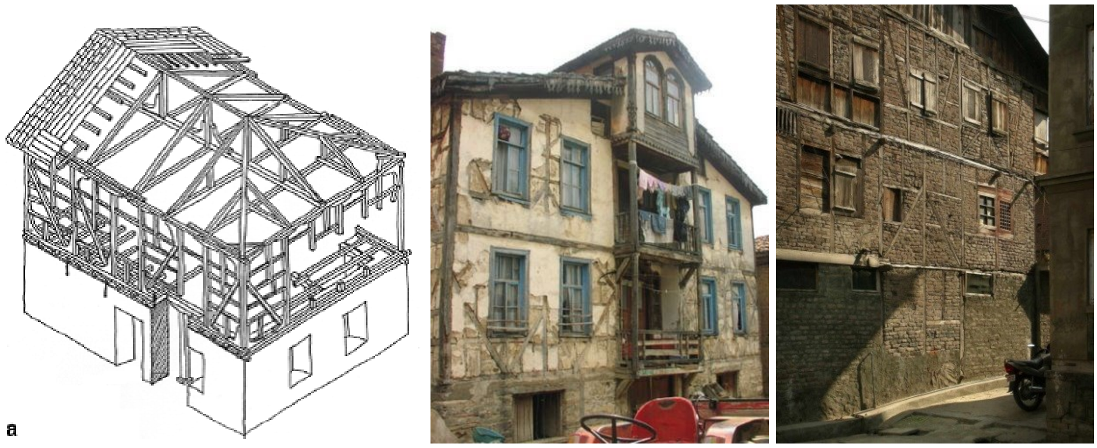
A brief overview on the history of timber frame buildings

The origin of timber frame structures probably goes back to the Roman Empire, as in archaeological sites half-timbered houses were found and were referred to as Opus Craticium by Vitruvius [2]. But timber was used in masonry walls even in previous cultures. According to [3-4] in the Minoan palaces in Knossos and Crete, timber elements were used to reinforce the masonry. Half-timbered constructions later spread not only throughout Europe, such as Portugal (edifícios pombalinos), Italy (casa baraccata), Germany (fachwerk), Greece, France (colombages or pan de bois), Scandinavia, United Kingdom (half-timber), Spain (entramados) etc., but also in India (dhaji-dewari) and Turkey (himis) [2][5]. In each country, different typologies were used, but the common idea is that the timber frame can resist to tension, contrary to masonry, which resists to compression, thus providing a better resistance to horizontal loads. Besides, the timber elements are viewed as a sort of confinement to the masonry structure, improving the mechanical properties to shear loads. In general, the cross section of the timber elements in the distinct case studies is very similar (approximately 10x12cm).

Timber frame buildings were common all over Greece in different periods, as reported by many authors [6-8]. Examples of this system are the monastic buildings in Meteora and Mont Athos, the post byzantine (Ottoman period) buildings in Central and Northern Greece and the traditional buildings in the island of Lefkas. These buildings consisted of a stone masonry ground floor plus one or two timber-framed masonry storeys (Fig. 1a), which represents a common disposition in timber frame buildings. Another innovation present in these buildings is the existence, at the ground floor, of timber columns stiffened by angles that constituted a secondary load bearing system in case of failure of the masonry walls, since they were connected to the timber-framed structure of the upper storeys [5].

In Germany, *fachwerk* construction was very popular and several examples of timber frame constructions are present all over the country. Different timber frame styles can be found, characterized by a varying number of storeys and geometry of the timber frame. In Germany, this construction system was introduced in the 7th century and it flourished particularly in the 16th and 17th century. Three main styles can be recognized (Alemannic, Lower Saxonian and Franconian), differentiating mainly in regards of the spacing between the elements, dimensions and disposition of the framing. An example of the German constructions is presented in the lexicon by Otto Lueger [9]

Another example of timber frame construction is the *casa baraccata* in Italy. After the 1783 earthquake in Calabria, authorities adopted construction methods similar to those imposed some decades before in Lisbon. The same construction technique, with slight changes, was also adopted after the Messina earthquake in 1908. In particular, Vivenzio proposed a 3-storey building with a timber skeleton aiming at reinforcing the external masonry walls, avoiding their premature out-of-plane collapse. The timber-framed walls constituted the internal shear walls, presenting a bracing system of S. Andrew's crosses, similar to what can be found in Lisbon [10]. A difference to the Portuguese solution is the continuity of the vertical timber posts from the foundation to the roof, being anchored in the foundation (especially in the buildings built after 1908) [11].



(a) (b) (c)

Fig.1. Some examples of timber frame buildings; (a) typical house of Lefkas island in Greece, built with the local aseismic technique [7]; (b) in Turkey - hatil at ground floor and himis in upper storeys [8]; (c) India - dhajji-dewari building in Kashmir [2].

Similar houses were also found in India and Turkey. Turkey is a prone seismic zone and is frequently subjected to strong earthquakes, meaning that the buildings need to be able to resist seismic actions. Besides, Turkey has an abundance of wood, as well as stone and clay, which promoted the growth of timber frame structures. The typical timber frame construction used in the upper floors is called *himis* and it is typically constituted of a timber frame filled with rubble or brick masonry [12] (Fig 1b). 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 lightweight, seismic resistant, economical structures, but were more disposed to decay [12]. Among India's traditional buildings, a half-timbered construction typology can be distinguished in the *dhajji-dewari* (patchwork quilt wall) system, which is a braced timber frame with masonry infill, frequently used for the upper storeys of buildings (Fig 1c). Buildings date as back as the XII century [2].

Timber frame construction has also been used in South America. In Peru, for example, the *quincha* presents a one-storey timber frame made of round or square wood (bamboo is often used) and filled with canes covered with earth and gypsum [13]. This type of construction was for example proposed by Peruvian experts for the reconstruction of Haiti after the severe earthquake of 2010 [14]. One of the few buildings which survived the earthquake was actually built with the construction system *quincha*. The reconstruction proposed is being done with the improved *quincha*. The posts are grounded in a concrete foundation, the infill consists of canes covered with clay and mud and, once dried, everything is covered with a cement plaster.

The Portugese Example. In Portugal, typical half-timbered structures are known as Pombalino buildings, which are old masonry buildings constructed after the 1755 Lisbon earthquake, which destroyed Downtown Lisbon. The new buildings took their name from the prime minister of the time, the Marquis of Pombal, who encouraged the reconstruction of the city. A Pombalino building is characterized by external masonry walls up to 5 storeys. The ground floor consists of stone masonry columns supporting stone arches and clay brickwork vaults and above the first floor develops an internal timber structure, named *gaiola* (cage), see Fig. 2. The *gaiola* consists of horizontal, vertical and diagonal bracing members, forming a three-dimensional braced timber structure. These timber-framed walls are filled with rubble brick or rubble stone masonry and act as shear walls. The length of a typical building is 8 to 16m and the width is about 10m. The internal walls of the *gaiola* (paredes de frontal) may have different geometries in terms of cell dimensions and number of elements, as it depends greatly on the available space and the manufacturer's customs [1]. The main horizontal and vertical elements are reasonably long, whereas the diagonal ones were very short. The timber elements are notched together or connected by nails or metal ties. Traditional connections used for the timber elements varied and could be mortise and tenon, overlapped, dovetail connections, and other types of notched connections. A wide range of sectional dimensions can be found in the elements: the diagonal members are usually smaller (10x10cm or 10x8cm), whilst the vertical studs and horizontal members are bigger (usually 12x10, 12x15cm and 14 x10cm or 15x13, 10x13 and 10 x 10cm).

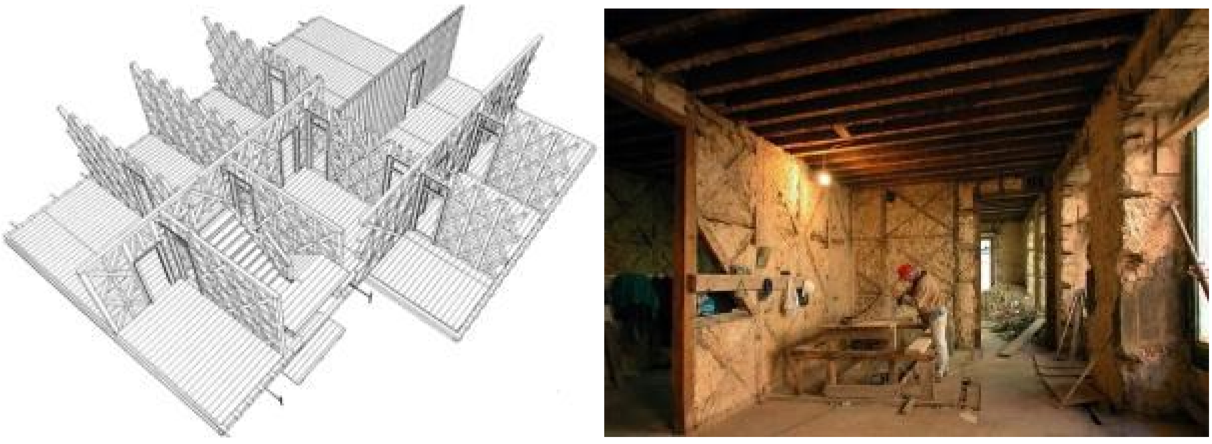


Fig 2. The Gaiola system in the Pombalino buildings [1].

The sectional dimensions of the elements are usually bigger for the lower storeys, decreasing progressively with the height of the building. The frontal walls have a width of 15-20cm, with a grout thickness covering the masonry infill of about 2.5cm but it could vary up to 5cm [1,15]. The frontal walls act as shear walls in the building but can be considered also as partition walls. The peculiarity of this type of building is that under a seismic event, it is admissible that the heavy masonry of the façades falls down, as well as the tiles of the roof and the plaster of the inner walls, but the timber skeleton should remain intact, keeping the building standing. It should be stressed that if the connections between the external masonry piers and the internal timber-framed walls are adequate, the out-of-plane collapse mechanisms of the external façades is also minimized. Some timber elements can be found in the external walls to promote the connection between the *gaiola* and the external masonry walls [16,17].

Seismic performance of timber frame structures – evidences from past earthquakes

Based on the analysis carried out on damage state of traditional timber frame buildings located in high prone seismic regions after important seismic events, it has been seen that very reasonable behaviour is exhibited by this structural system in distinct countries with high seismicity [18]. Timber frame structures combine the best features of masonry and timber, offering a better overall behaviour of the buildings under seismic actions. With this respect, it is important to consider that the state of conservation of the traditional buildings can influence its seismic behaviour.

After the strong earthquake in 2003 in Lefkada, a high prone seismic region, it was observed that in spite of damages developed in the traditional buildings, they were not so severe than the ones observed in reinforced concrete buildings and no colapse of traditional buildings was recorded.The damages observed included vertical and diagonal cracks and, in some cases, colapse of the stone masonry walls at the ground floor, shear cracks at the interface between timber frame and masonry infill, which in certain extent promoted the out-of-plane collapse of infill (Fig. 3a), crushing of the infill masonry. Almost no damage was found in the wood elements of the timber frame [7]. Another example where the efficiency of timber frame structures was tested consists of the traditional timber frame buildings in Turkey, already described. Turkey is frequently exposed to severe earthquakes being one of the few countries with the shortest return period in earthquakes causing often loss os lives [14]. Different authors have pointing out the reasonable earthquake resistance of timber frame buildings, specially with comparison with other structural systems such us masonry or reinforced concrete structures (Fig 3c), namely during the 1894 Istambul earthquake, 1970 Gediz earthquake and more recent 1999 Marara (Kocaeli) earthquake [14]. According to Gülhan and Güney (2000) [14], in Kocaeli-Gölcük, in the Sehitler distric, 51% of the buildings are RC buildings (up to 7 storeys), while the rest are traditional (either half-timbered or timber-laced masonry or plain masonry up to three storeys).

(a) (b) (c)

Fig. 3. Examples of damages in timber frame buildings; (a)) out-of-plane collapse of masonry infill (Lefkada, Greece) [6]; (b) comparison of damages to traditional and modern building after the 1999 Duzce earthquake; (c) failure of connection in timber frame (1999 Kocaeli earthquake [14].

From these, only 0.5% of the traditional structures presented heavy damages or collapsed against 7.4% of the RC structures, 0.6% of the traditional structures presented moderate damage versus 8.6% of the RC and 10% and 16.5% respectively presented light damages. In all the mentioned earthquakes, low number of total colapses of traditonal buildings were recorded, even if light to severe damage can develop depending on the conservation of the structure, on the materials, and on the structural features of the system. The typical damages in timber frame buildings under seismic actions include: (1) cracking and failure of plaster as the result of the deformation of the braced elements and posts. When reduced space of the posts exists no propagation of the cracking occurs for the masonry infill; (2) loosening and failure at the connections (Fig. 3c). In fact,the connections take a central role on the seismic behavior of traditional timber frame buildings as they are the elements keeping the structure together during the earthquakes, being understabdable that important deformations and damages can develop; (3) large lateral displacents, which can result from soft-storey mechanism, resulting from the changes carried out on the traditional buildings at the first floor related to the removing of timber brace elements and studs aiming at having free spaces for commecial purposes.

In addition, the earthquakes of India 2001 and El Salvador 1986 are other two examples where the timber-laced masonry buildings and the *Bahareque* timber frame buildings behaved considerably better than reinfored concerete or unreinforced masonry [18]. The heavy damage and inadequacy of timber frame building under earthquakes, as ocurred in Nicaragua 1936, can often be attributted to the poor condition of the connections due to inadequate conservation. More recently, during the earthquake of Haiti in Januray 2010, it was seen that a great number of concrete block and reinforced concrete buildings were heavily damaged, resulting in the loss of a dramatic number of human lifes and in a huge economical impact in the economy [19]. Contrarily, the behavior of traditional timber frame buildings did not exhibit so much severe damage. Both the braced timber frame and the colombage, with more flexible, energy dissipating systems tended to perform best than the other structural systems (masonry and reinforced concrete) [19].

Experimental research on timber frame walls

In spite of timber-frame walls are very common all over the world, behaved reasonably well during past earthquake events, very little information is available on their experimental seismic behaviour that enable to understand the resisting mechanisms under lateral loading. In fact, this type of construction system has not been taken into great consideration from the scientific research community but a great number of historical buildings are actually timber frame, 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 and modifications introduced in the structures makes their seismic assessment a relevant research issue.

With this respect, only in the last decade experimental studies have carried out in different countries for the evaluation of the in-plane lateral performance of distinct types of timber frame walls. Therefore, this section aims at giving an overview on the experimental analysis of timber frame walls under in-plane cyclic/monotonic loading by presenting the main outocomes.

Experimental research on *frontal* timber frame walls. In relation to Pombalino timber frame walls, few experimental information is available until now. From the *frontal* walls point of view, the first experimental work carried out at laboratory was carried out by Santos (1997) [20], in the scope of a rehabilitation program of ancient masonry buildings. Three specimens of real walls were taken from an existing building which was going to be demolished and tested under static cyclic loads. It should be noticed that no vertical load was applied. The hysteresis loops of the tested wall, shown in Fig. 4a, are indicative of the good deformation capacity and energy dissipation capacity of the structure. Cyclic tests were also carried out by Meireles *et al.* [21] on walls similar to the ones tested by Santos (1997) [20]. The wood specie selected was pinus pinaster, a typical Portuguese softwood, modern nails were used but were assembled according to what is seen in existing walls (number and positioning).

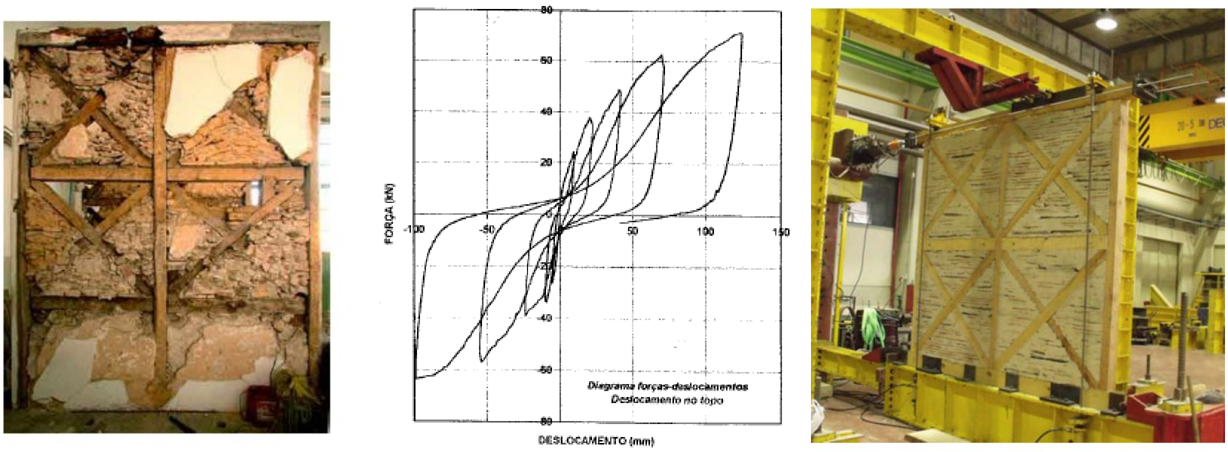
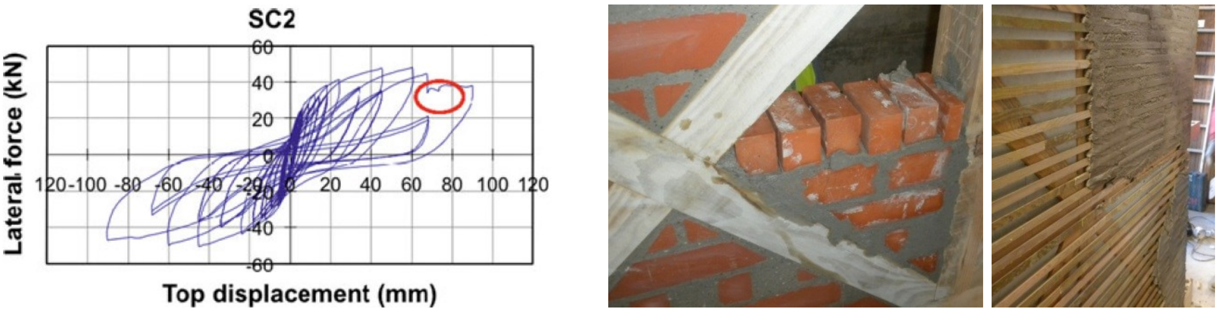


Fig. 4. Experimental testing of frontal walls; (a) tests carried out by Santos (1997) [20]; Specimen used by Meireles et al. (2012) [21].

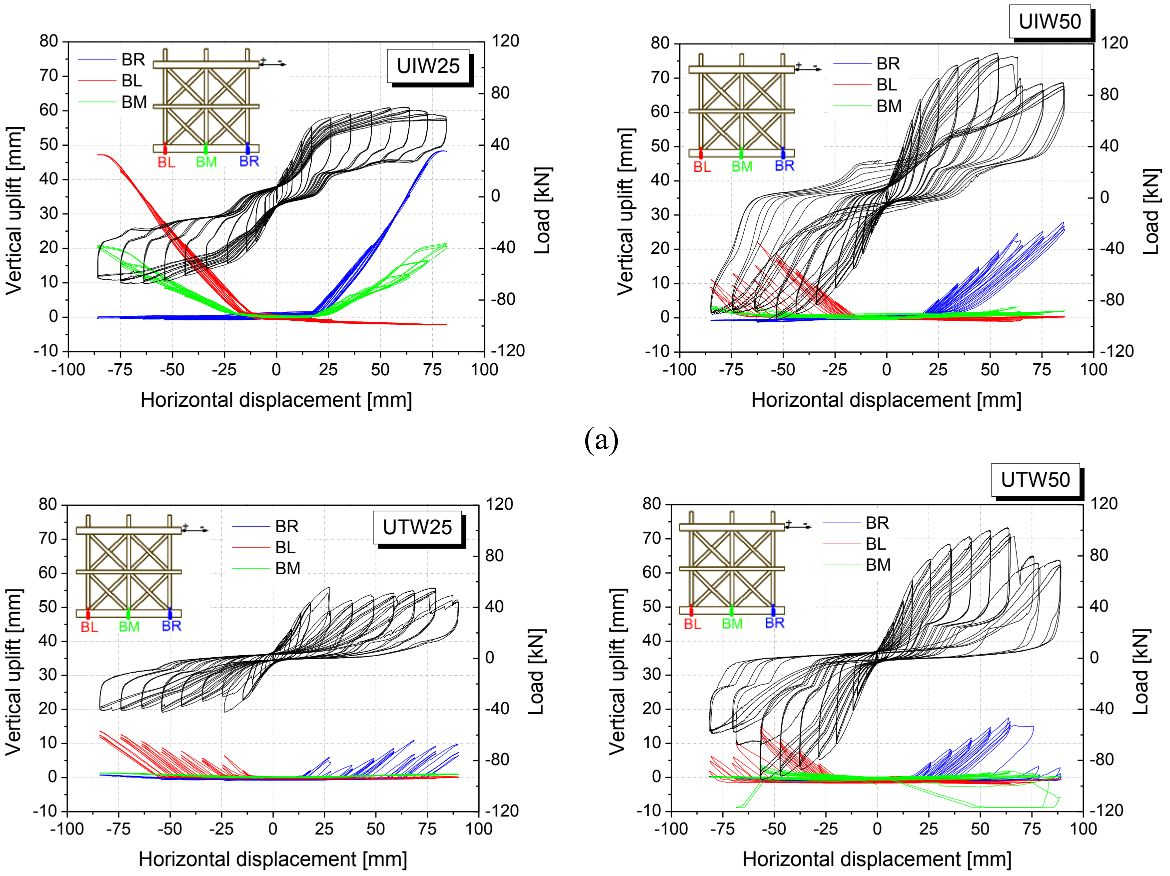
For the beams and post a cross section of 12x8cm^2 was used and for the diagonals a section of 10x7cm^2 were adopted. Overlapped connections were considered between beams and vertical posts and between diagonal bars, being applied additionally two nails. The diagonal bars are connected to the beams and posts through nails. A nail was also used to connect the diagonal braces. For the infill material it was decided to use brick masonry made with low strength hydraulic lime. The walls were tested under cantilever boundary configuration, as the top of the wall could rotate. The bottom beam was fixed to the reaction structure so that uplift was avoided. The vertical load applied was about 80kN aiming at simulating the dead and live load of a typical three stories and the ground floor by means of four hydraulic jacks. The tests were carried out under displacement control by using the Curee loading protocol. The hysteresis loops obtained for the two *frontal* walls tested allow seeing that in-plane lateral response is characterized by a considerable non-linear behaviour, with the hysteresis loops predicting reasonable energy dissipation (Fig. 5a). The response is also characterized by pinching, which is associated to cumulative damage at the connections and progressive increase on the plastic deformations, similarly to what was also recorded in the tests of Santos (1997) [20]. The collapse of the walls occurred for a lateral drift of 3.5%. In-plane cyclic tests were carried out by Poletti and Vasconcelos (2013) [22] on the same type of walls. In this case, the dimension of the braced diagonal cell is lower, leading to a total height and a length of the wall 8% lower. Only one nail was used in all overlapped connections and regular brick masonry was considered as infill material. Alternatively, lath and plaster was adopted as infill material, see Fig. 5b. Besides the timber frame infill walls, also empty timber frame walls were tested. The vertical load was applied directly to the posts. Two levels of vertical loads were considered, namely 25kN and 50kN per post. The typical load-displacement diagrams are presented in Fig. 6 for brick infill and empty timber frame walls with brick masonry for the two levels of vertical load. From the analysis of these diagrams, it is possible to observe that: (1) the timber frames filled with masonry and lath and plaster presents similar behavior, being the predominant resisting mechanism characterized by flexure, corresponding to the uplift of the lateral posts and rotation of the wall.



(a) (b)

Fig. 5. (a) Typical force-displacement diagrams [21]; (b) infill material for frontal walls [22].

This resisting mechanism leads to plastic deformation of the nails placed at the overlapped bottom connections, which should be responsible for the unload branches characterized by a plateau; (2) the timber frame walls exhibit typical shear behaviour being the force-displacement diagrams characterized by pinching resulting from the cumulative deformation observed in the walls, particularly at the connections. The failure mode is characterized by the shear collapse of the central connections; (3) the infill materials (masonry brick and lath and plaster) influence the resisting mechanism of the timber frame walls. The resisting shear mechanism of plane timber frame wall is replaced by flexural rocking mechanism in case of infill material is added. This act as confining elements, conditioning the deformation of the connections; (4) the vertical load applied in the posts influences the lateral resistance and the overall behaviour of the walls. The increase on the vertical load results in the increase of the lateral resistance. On the other hand, higher vertical loads lead to the decrease of the vertical uplift of the posts, mainly in case of filled walls, meaning that the flexural rocking mechanism that prevails in the response of the lowest vertical load is reduced. It is possible that the higher stiffness of the brick masonry used in case of Poletti and Vasconcelos (2013) [22], results in the higher stiffening effect of the connections leading to predominant flexural behaviour, contrarily to shear behaviour achieved by Meireles et al. (2012) [21]. This appears also to be valid for the lateral resistance, as the lateral strength obtained by the authors is higher than the one pointed out by Meireles *et al.* (2012) [21], taking into account that the same vertical load was applied. The predominant flexural behaviour found for the lowest vertical pre-compression levels was also obtained by Gonçalves *et al.* (2012) [23], who carried out in-plane cyclic tests in the same walls of Poletti and Vasconcelos [22]. It should be noticed that in these two works only the brick masonry was not the same. In all mentioned experimental works the timber frame detach from the masonry for increasing lateral displacements. In the tensile part of the frame the masonry does not work at all, being only active in the neighourhood of compression strut of the oposite side.



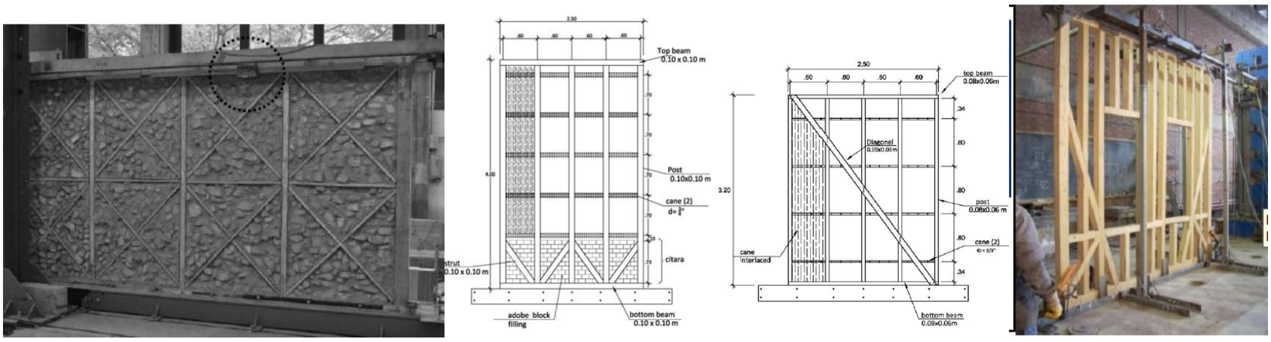
(a)

(b)

Fig. 6. Force-displacement diagrams obtained for *frontal* walls tested by Poletti and Vasconcelos (2013) [22]; (a) walls filled with brick masonry submitted to a vertical load of 25kN/post and 50kN/post; (b) empty walls submitted to a vertical load of 25kN/post and 50kN/post.

The detahcment pointed out by Meireles et al. [21] is more associated to the shear deformation of the timber frame. In terms of lateral drift, the values obtained by Poletti and Vasconcelos (2013) [22] for all walls was close to 4%, meaning that it was a little higher than the value pointed out by Meireles et al. (2012) [21] of 3.5%. It should be mentioned that the values obtained by the authors could be even higher in some walls, particularly the ones submitted to the lowest levels of pre-compression, as the maximum displacement did not correspond to the collapse of the walls. In relation to the values of equivalent viscous damping, it should be mentioned that the authors found higher values for low lateral drifts when compared to the values found for higher lateral drifts, being in average 0.1 for infilled timber frame walls and 0.12 for timber frame walls in case of high lateral drifts. These values are of the order of the ones found by Gonçalves *et al.* (2012) [23], on similar traditional Portuguese *frontal* walls, which obtained values of viscous damping for low values of drift of 0.17-0.20 for infill walls and 0.19-0.20 for empty timber frame walls. The values then decreased to 0.11-0.13 and 0.10-0.11 respectively, confirming the trend of having higher values for low drifts, then decreasing values. The values of the equivalent viscous damping obtained by Vasconcelos *et al.* (2013) [24] for 1:2 reduced scale "frontal" walls tested under in-plane cyclic loads was about 0.15. This higher value can possibly be atributed to the distinct "frontal" walls typology and connections: additonal vertical and horizontal bars in the braced cells and mortise-tenon connections between beams and posts. From this work it was possible to observe that the equivalenet viscous damping depends on the resisting mechanism, being higher when shear response predominantes. In these walls lateral drifts of about 3.5% were obtained, being comparable with the values obtained in the oter studies.

Experimental research on other timber frame systems. In this section a very brief overview is provided in relation to experimental research carried out on timber frame walls that are characteristic of different countries, namely Peru and Turkey (Fig.7). Some notes are also given about the work carried out on the construction system used in the reconstruction of Haiti after the earthquake of January 2010 [25]. The traditional timber frame walls used in the reconstruction of houses in Haiti, whose shape is similar to *frontal* walls of Pombalino buildings (Fig. 8a), exhibit a clear nonlinear behaviour under in-plane lateral cyclic loading with important pinching effect. The shape of the hysteresis is very similar to the one obtained in the experimental results pointed out by Meireles *et al.* (2012) [21]. In this work it is possible also to assess the influence of the infill rubble stone masonry. Similarly to what was pointed out by Poletti and Vasconcelos [22] and Goçalves *et al.* [23], the addition of an infill material leads to the increase on the lateral strength and stiffness. From the monotonic envelop it appears that the timber frame wall without infill has more ductility. The force-displacement diagrams obtained in the *quincha* walls (Fig. 8b) are also characterized by nonlinear behaviour and pinching effect. These walls presented a remarkable capacity to deform nonlinearly, having great lateral drifts: 7.5% for the walls with Citara (struts at the base of the wall, Fig.7b - left) and 9.375% for the wall with diagonal (Fig. 7b - right).



(a) (b) (c)

Fig. 7. Timber frame walls: (a) system used in the reconstruction of Haiti [25]; (b) *qincha* walls [26]; (c) timber frames characteristic of himis construction, Turkey [27].

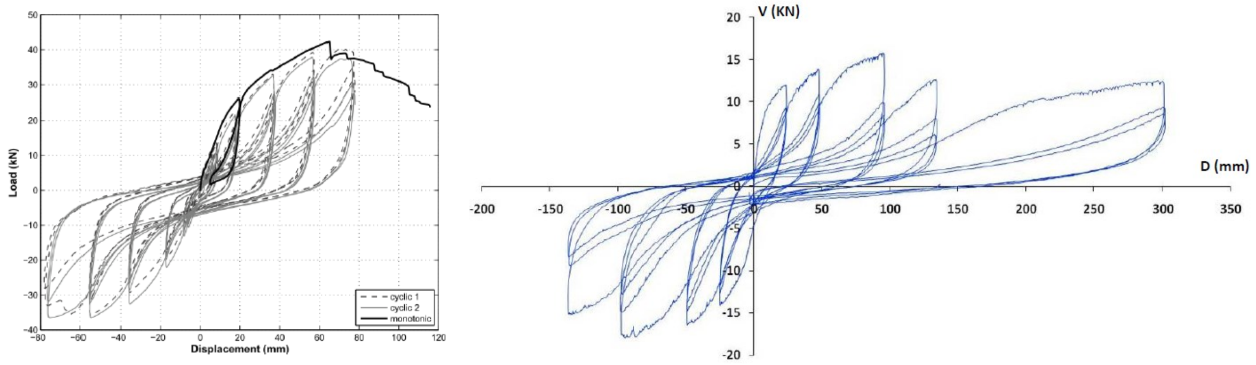


Fig. 8. Typical force-displacement diagrams; (a) walls used in the reconstruction of Haiti [25]; (b) *qincha* walls [26].

The experimental work carried out by Aktas *et al.* (2012) [27] on in-plane cyclic testing of timber frames characteristic of himis construction, unfilled, and filled with brick masonry and wood laths and plaster (bagdadi), revealed that the behaviour the timber frames is very controlled by the behaviour of the connections, being the damage concentrated at the connections. Besides, the higher capacity to deform in the nonlinear range is confirmed by the great lateral drifts of about 6% in case of empty frames and 5.5% in case of brick masonry infill and 4.9 in case of lath and plaster (bagdadi cladding). Additionally, it was seen that according to what was pointed out by other authors [22][25], the addition of an infill material and cladding is responsible for the increase on the lateral stiffness and lateral resistance.

Concluding remarks

This paper aimed at making an overview of the seismic behaviour of the traditional timber frame construction based both on the evidences from the past earthquakes and from the recent experimental works on in-plane cyclic testing. From the analysis made, it is observed that there are several evidences of the very reasonable behaviour of timber frame construction submitted to important seismic events. This is in certain extent also observed from the experimental works, from which it is possible to observe timber frame walls exhibiting large capacity to deform in the nonlinear regime with remarkable lateral drifts with controlled damages under in-plane cyclic loading. In general the in-plane behaviour is considerably better than unreinforced masonry walls, used in vernacular architecture in several countries with important seismicity, meaning that traditional timber construction deserve to be conserved and can be viewed as a true alterative for reconstruction and strengthening purposes of vernacular traditional construction.

References

[1] Mascarenhas J. Construction systems – V. (in Portuguese). Lisbon: Livros Horizonte; 2004.
[2] Langenbach R. DON'T TEAR IT DOWN! Preserving the earthquake resistant vernacular architecture of Kashmir. New Delhi: UNESCO; 2009.
[3] Tsakanika-Theohari E. The constructional analysis of timber load bearing systems as a tool for interpreting Aegean Bronze Age architecture. in Proceedings of the Symposium '*Bronze Age Architectural Transitions in the Eastern Mediterranean: Diffusion and Diversity*', 07.-08. 05. 2008 in Munich (Weilheim 2009): 127-142, 2008.
[4] Tampone G. The restoration of timber structures (in Italian). Milan, Libreria Tecnica Hoepli, 1996.
[5] Cóias V. Structural rehabilitation of old buildings (in Portuguese). Lisbon: ARGUMENTUM, GECoPRA; 2007.
[6] Makarios T, Demosthenous M. Seismic response of traditional buildings of Lefkas Island, Greece. Engineering Structures, 28, 264-278: 2006.

[7] Vintzileou E, Zagkotsis A, Repapis C, Zeris Ch. Seismic behaviour of the historical structural system of the island of Lefkada, Greece. Construction and Building Materials, 21, 225-236: 2007.

[8] Tsakanika-Theohari E, Mouzakis H. A post-Byzantine mansion in Athens. The restoration project of the timber structural elements. World Conference on Timber Engineering, Riva del Garda, Italy, June 20-24 2010.

[9] Lueger O. Encyclopedia of total technology (in German). 1894.

[10] Copani P. Timber-frame buildings in Scandinavia: high deformation prevent the system from collapse. From Material to Structure - Mechanical Behaviour and Failures of the Timber Structures ICOMOS IWC - XVI International Symposium. Florence, Venice and Vicenza 11-16 November 2007. (Available at http://www.icomos.org/iiwc/2007.htm)

[11] Tobriner S. The baraccata house: an antiseismic system in the XVIII century Calabria (in Italian). Costruire in laterizio 1997; 56: 110-115.

[12] Bianco A. The baraccata house. Guide to desing and restauration site (in Italian). Rome: GB EditoriA; 2010. p. 19, 29, 60.

[13] Gulkan P, Langenbach R. The earthquake resistance of traditional timber and masonry dwellings in Turkey. *13th World Conference on Earthquake Engineering.* Vancouver, 2004.

[14] Gülhan D, and Güney IÖ. The behavior of traditional building systems against earthquake and its comparison to reinforced concrete frame systems: experiences of Marmara earthquake damage assessment studies in Kocaeli and Sakarya. Proceedings of Earthquake-safe: Lessons to be Learned from Traditional Construction, Istanbul, Turkey, 2000. (Available at: http://www.icomos.org/iiwc/seismic/Gulhan.pdf)

[15] Jurina L, Righetti M. Traditional building in Peru. XVI IIWC International Conference and Symposium, Florence-Venice-Vicenza, 11th-16th November 2007.

[16] Pinho FFS. Walls of old buildings in Portugal (in Portuguese). Lisbon: LNEC; 2000.

[17] França JA. Pombaline Lisbon and the illuminism (in Portuguese). Lisbon: Bertrand; 1983.

[18] Langebach R. From “Opus Craticium” to the “Chicago frame”: Earthquake-resistant traditional construction, International Journal of Architectural Heritage, 1, 29-59, 2007.

[19] Langebach R, Kelley S, Sparks P, Rowell K, Hammer M, Julien O. Preserving Haiti’s Gingerbread Houses. 2010 Earthquake Mission Report. World Monuments Fund. December 2010

[20] Santos S. Tests of Pombalino walls (in Portuguese). Lisbon: LNEC; 1997. Nota Técnica Nº 15/97-NCE.

[21] Meireles H, Bento R Cattari, S, Lagomarsino, S. A hysteretic model for “frontal” walls in Pombalino buildings, Bulletin of Earthquake Engineering, 10(5), 1481-1502, 2012.

[22] Poletti E, Vasconcelos G. Oliveira DV, influence of infill on the cyclic behaviour of traditional half-timbered walls, International Conference on Rehabilitation and Restoration of Structures, Chennai, India, 13-16 February, 2013.

[23] Gonçalves A, Gomes Ferreira J, Guerreiro L, Branco F. Experimental characterization of Pombalino “frontal” wall cyclic behavior, 15th World Conference on Earthquake Engineering, 24-28 September, Lisbon, 2012.

[24] Vasconcelos G., Poletti E., Salavessa E., Jesus A., Lourenço P., Pilaon P. In-plane shear behaviour of traditional timber walls, Engineering Structures, 56, 1028-1048, 2013.

[25] Vieux-Champagne F. Grange S, Sieffert Y, Daudeville L. Experimental analysis of seismic resistance of shear walls in traditional Haitian houses, 15th World Conference on Earthquake Engineering, 24-28 September, Lisbon, 2012.

[26] Torrealva D, Vicente E. Experimental evaluation of seisic behavior of Quincha walls from the historic centre of Lima – Peru, 15th World Conference on Earthquake Engineering, 24-28 September, Lisbon, 2012.

[27] Aktaş YD, Akyüz U, Türer A, Erdil B, Güçhan NS. Seismic Resistance Evaluation of Traditional Ottoman Timber-Frame *Hımış* Houses: Frame Loadings and Material Tests. Earthquake Spectra, 2013. doi: http://dx.doi.org/10.1193/011412EQS011M.