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INVESTIGATION OF A NOVEL TIMBER-MORTAR CONSTRUCTIVE SYSTEM

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ABSTRACT: Timber constructions are well-know because are able to guarantee structural safety and easy assembling as well as high level of thermal insulation and living comfort. The new challenge is to enhance the use of local resources and starting to design the whole building in order to permit to dismantle and reuse/recycle the different elements/materials at the end of building-life. A constructive technology that can answer to all the aforementioned requirements is represented by a timber-mortar composite structures recently proposed. The use of timber-masonry structures belongs to the European tradition and different typologies of wooden frame infilled with masonry or with clay/mortar have been used all over the world. This paper analyses the mechanical behaviour of a new concept of timber frame wall infilled with lime mortar: experimental results show that, for low-rising buildings, the presented system is a valuable alternative to timber shear-walls (e.g. Light Frame Timber or Cross Laminated Timber). Furthermore, the studied system permits to use small-section timber elements that can be easily obtained sawing local wood; moreover, indoor air quality and living comfort are guaranteed using, for the whole construction, only few natural row materials such as wood, lime, clay and hemp.

KEYWORDS: Use of local wood, Wooden frame, Timber-mortar wall, Reuse-Recycle, Experimental test.

1 INTRODUCTION

In the last decades the use of timber in constructions has constantly increased, driven by the physical-mechanical properties of wooden products: the very high strength-to-density ratio of wood makes it extremely competitive for buildings constructions in seismic-prone areas. Moreover, the thermal properties of wooden panels can be exploited to improve energy efficiency of new residential buildings. Light-Frame Timber (LFT) and Cross Laminated Timber (CLT) represent the most widely used timber technologies, in particular, LFT give the possibility to prefabricate the entire wall (structure, insulation and also electrical and plumbing systems) while CLT panels are becoming strong engineered and industrialized products. Recently both research institutes and the productive sector have been starting to study and propose timber constructive systems able to ensured structural safety, high level of thermal/acoustic insulation and, at the same time, to improving the living comfort (i.e. optimal thermo-hygrometric indoor conditions and quality of air indoor). Contextually, the main challenge is to re-design the entire building process in order to increase the use of wood grown in areas close to construction site. The use of local resources (e.g. wooden row material) and an appropriate study of the end-of-life phases as the dismantling/disassembling and the reuse/recycle are critical points that have to be considered.

Figure 1: *Example of timber-mortar constructive system use; prefabricated only-timber frames assembled on-site (above) and building during the pouring of lime mortar (below)*

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A valuable solution is to distinguish the different function of the building elements adopting engineered materials and high-technology connections for the bracing systems, able to guarantee the stability of the structure even in case of earthquake, while secondary elements could be obtained with timber elements composed by row wooden material. Another way is represented by the use of only-natural material (i.e. wood, mortar, brick, etc…) and, where necessary, steel connections which have to be separated and recycled as used-iron at the dismantle phase. With these materials it is possible to obtain all the building elements both structural/non-structural walls and horizontal floors/roof.

This paper will discuss the possibility to erect low-rising buildings with a novel constructive system named "*Nidus*" that belong to the second category being the whole building composed by timber elements infilled with mortar. More than 20 low-rise buildings (up to 3 storeys) have been realized in Italy in the last decade with this technology. Starting from the state of the art, the new timber-mortar system will be presented and results of an experimental mechanical tests campaign will be discussed.

2 STATE OF THE ART

Timber frame structures with masonry infill, also called "half-timber" buildings, have been used all over the world. The main reasons for this widespread diffusion are certainly the easy access to materials, the simple construction method and the good seismic response. Examples of this kind of structures can be found in many European countries, especially in seismic prone areas: "*fachwerk*" (North-Central Europe), "*gaiola pombalina*" (Portugal), "*casa baraccata*" (South Italy), "*lefkada*" (Greece), "*hatil**,** himiş* and *bağdadi"* (Turkey). Other examples of timber frames with mansory infill can be found in other regions all over the world: *"taq* and *dhajji-dewari"* (Kashmir, India), "*assam-type structure"* (Himalayan region), *"chuan-dou timber frame"* (South-west of China), *"kay peyi"* (Haiti) and *"tapial, adobe and quincha"* (South and Centre America).

As pointed out by Langenbach [1], it's relevant to observe that some of these structural systems were specially developed and selected as earthquake-resistant construction. In Lisbon (Portugal), after a disastrous earthquake in 1755, the construction system called "*gaiola pombalina*" was used for the reconstruction of the city. This structural system consists of a three-dimensional wooden frame, braced with wooden elements and filled with stones and bricks. The inspiration for this technique came from the observation that the half-timber type constructions had withstood better the earthquake [1] than the "only" masonry structures, thanks to their deformability. In the southern part of the Calabria Region (Italy), after an earthquake in 1783, a system constituted by masonry reinforced with timber frames, called "*casa baraccata*", was indicated from the government as an essential requirement to ensure safety [2]. An comprehensive collection of articles concerning the seismic behaviour of *half timber buildings* in the Mediterranean area, experimental tests and numerical modelling is presented by Ruggieri et al. [3]

Recent seismic events (Turkey in 1999, Greece in 2003, Kasmir in 1967 and 2005, Haiti in 2010) have highlighted the good seismic response of these mixed constructions. For this reason, some research projects have been conducted in order to improve the knowledge regarding the seismic resistant behaviour of this kind of traditional wood frame structures. Makarios et al. [4] studied the seismic response of the traditional buildings of Lefkas Island in Greece observing a good seismic behaviour. Dogangun et al. [5] and Gülhan et al [6] observed an excellent seismic response of traditional buildings after the earthquake occurred in Kocaeli and Duzcedel (Turkey) in 1999. Kaushik et al. [7] reported about the better behaviour of traditionally constructed timber-masonry structures compared to reinforced concrete structures during the Sumatra earthquake in 2004. Kaushik et al. [8] observed that both masonry and reinforced concrete buildings showed poor performance during the Sikkim (India) earthquake of 2006, while traditionally constructed half-timber houses showed acceptable damage.

Several experimental studies on the behaviour of traditional half-timbered walls are available in literature. Four modules of a timber crossed frame without masonry infill and three identical modules with masonry infill have been tested by Ferreira et al. [9] under horizontal and vertical load and compared with numerical models. Three different types of half-timbered walls (unreinforced, retrofitted with GFRP sheets and filled with brick masonry) have been tested by Vasconcelos et al. [10], the latter showing high values of ductility. Half-timber walls build in real scale were tested under cyclic load by Poletti et al [11] considering two different infill typologies, as well as the possibility of having no infill, showing that the presence of infill increases the cyclic stiffness, as well as the energy dissipation and the ductility. Two full-size of a "*gaiola pambolina*" walls, were tested in a cyclic manner by Dutu et al. [12] showing a good in-plane behaviour of the timber–framed masonry system and significant deformation capacity. Meireles et al. [13] conducted cyclic shear testing to study the hysteretic behaviour of the interior wooden walls of the half-timber "*gaiola pambolina*" building in Portugal, showing non-linear load–displacement responses and high ductility. A full-scale replica of "*casa baraccata*" wall has been tested under quasi-static cyclic load by Ruggieri et al. [14] and Sandak et al. [15], at CNR-IBE laboratory in San Michele all'Adige – Italy. Ali et al. [16] conducted in-plane quasi-static cyclic tests on three full-scale "*dhajji-dewari"* building walls and monotonic tensile and bending tests on connections, showing that the masonry infill does not increase the lateral load capacity, but it has an effect on the energy dissipation capacity of the system. Two distinct geometrical variations of "*quincha*" were tested by Quinn et al. [17] with and without the infill, showing that the infill increases stiffness and capacity, 4.5 and 2 times respectively. Chand et al. [18] conducted an experimental campaign on seven different connections generally adopted in "*assam-type*" houses using cyclic tests and pull-out tests showing high deformability and ductile behaviour. Cyclic tests were performed by Liang et al [19] on three "*Chuan-dou*" timber frame models with a scale of 1:2 with and without infill. Experimental analysis of seismic resistance of Haitian timber-framed structures with stones-earth infill called "*kay peyi*" were performed by Vieux-Champagne et al. [20] at CNR-IBE Laboratory demonstrating the high ductility of the filled wood structures.

Novel composite wooden-masonry or wooden-mortar walls have been proposed and used in different European countries. Bettini [21] studied the use of partitioned *adobe* infills in association with timber frames. Recent studies have highlighted the possibility to use hemp cement as infill in low-rise timber buildings [22-26].

All the aforementioned studies agree with the fact that the composite timber-masonry or timber-mortar structures lead to an optimal overall behaviour: framed timber structure is loaded by vertical/horizontal loads and, at the same time, confines the masonry/mortar infill which collaborate in order to stiffen the wall and to transmit the vertical/horizontal loads to the foundation; furthermore, the infill element is able to guarantee good thermal performances during the summer season, thanks to the mass given by infilled material.

3 THE COSTRUCTIVE SYSTEM

Nidus timber structure is given by "balloon-frame" prefabricated wooden truss elements (maximum width 2,5m) modules that are assembled at the factory and jointed together at the construction site.

Once defined the architectural concept of the building, timber prefabricated modules, that will compose the different walls, have to be designed. A complete 3D model (Figure 2) have to be implemented and all the wooden elements, needed to assemble the prefabricated truss, have to be drawn and verified.

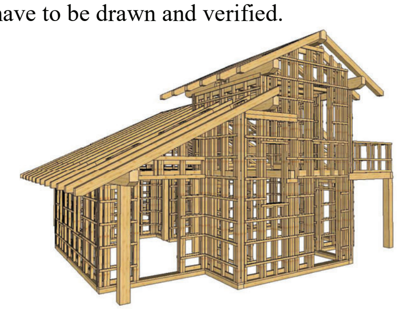

Figure 2: *Nidus constructive system, 3D model*

According to the 3D design, the carpentry/factory can cut manually or through a CAD-CAM process and CNC machines all the small-section wooden elements. Typically, the vertical wooden elements are 80mm x 80mm, while horizontal and diagonal are 80mm x 30mm. An horizontal beam is expected at the inter-storey level in order to support the floor beams (e.g. 160mm x 240mm) that will be inserted and screwed to the continuous vertical elements at the construction site.

Different members are jointed together with 5mm diameter screws according to the assembling drawings (Figure 3): the carpentry/factory can use the well-known steel modular frame developed for LFT prefabrication.

Figure 3: *Nidus balloon-frame prefabricated modules*

The preassembled elements, identified by a numerical code, that clearly indicate the position, can be easily moved by simply use of lifting belts. Once placed in the right position the studs are anchored to the pre-casted concrete foundation with commercial hold-down (uplift forces) and the bottom beams is connected to foundation with standard concrete bolts (shear forces). Modules can be screwed one to each other in order to avoid gap between the vertical elements. Typically the last horizontal closure is a standard timber inclined beams roof (Figure 4). By this doing in a couple of days the whole structure is erected.

Figure 4: *On construction site: Nidus modules assembled*

In order to obtain the complete wall-system, wooden-cement panels have to be stapled on the external faces of the timber frame. Finally, the empty area between panels is infilled with mortar composed by a mix of lime, perlite and hemp (Figure 5) characterized by a density equal to 350÷450 kg/m^3, as the softwood used for the structure.

Figure 5: *Detail of Nidus wall during mortar casting*

Is important to note that, according to the *Nidus* constructive systems, the casted lime mortar creates a continuous layer that wrap the entire building running both on the vertical external surface (walls) both on the external horizontal surface (roof) giving a unique layer of

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thermal insulation and natural air tightness (no membrane/tapes are required), see Figure 6.

Figure 6: *Lime mortar casted in the space between floor beams (up) and on the top of the roof (below)*

4 FULL-SCALE TESTS

Full scale tests were carried out to investigate the mechanical behaviour of the timber-mortar wall system in particular *only-timber* frame (Figure 7, left) was tested according to the EN 594:2011 [27] monotonic procedure, furthermore complete *wall-systems* (Figure 7, right and Figure 8) were tested both according to monotonic and cyclic protocols, EN 594:2011 [27] and EN 12512:2001 [28], respectively.

Figure 7: *Full scale tests on only-timber frame (left) and complete-wall system (right)*

The *only-timber* specimen (Figure 7, left) is a timber frame composed by small wooden elements (vertical elements 80mm x 80mm, horizontal elements 100mm x 28mm and diagonal elements 60mm x 28mm) assembled with 5mm diameter screws. In order to realize the complete *wall-system* specimens (Figure 8), the procedure described in Section 2 was applied to two further *only-timber* specimens: external panels were stapled and the mortar was casted; two months later, tests were performed. Specimens were realized respecting exactly the procedure given by *Nidus* constructive system.

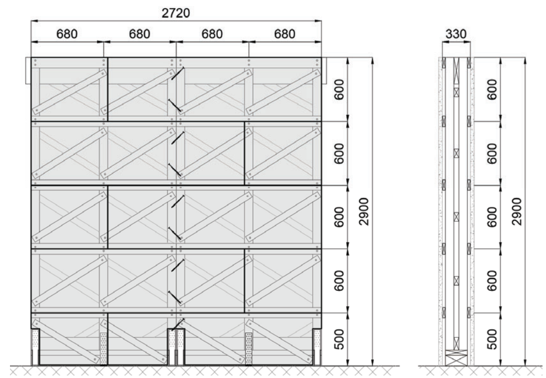

Figure 8: *Complete wall-system, geometry and connections*

Consistently with the provisions reported in EN 594 a series of transducers was applied to the tested specimens, as shown in Figure 9. A Linear Variable Displacement Transducer (LVDT), named LPM057, measured the horizontal displacement at the top corner of the wall. According to [27] these displacements are required to calculate the racking stiffness of the specimen. Two LVDTs (LPM052 and LPM053) measured the diagonal displacements of each module which forms the wall. A LVDT (LFV033) was placed at the centre of the wall in order to measure the relative vertical displacement between the two modules. Two LVDTs, LPM055 and LPM056, measured the uplift of the wall at the hold-downs positions, as shown in Figure 6. In cyclic test the same transducers were applied.

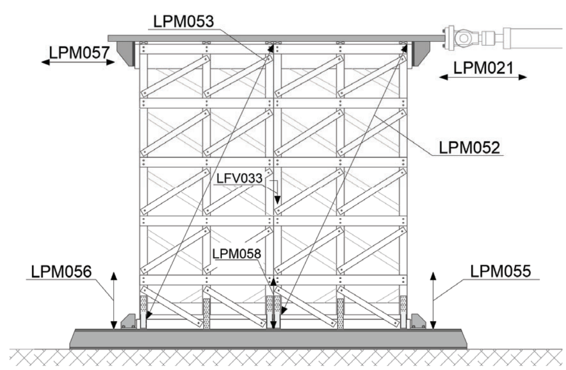

Figure 9: *The complete-wall system at the end the test*

The timber frame was anchored to the steel foundation with 4 couples of hold down (4 hold downs at both side of the wall), in order to avoid rigid rotation due to uplift forces, while the horizontal sliding is prevented by a steel rigid element (bolted to the steel foundation) in contact with the bottom wooden beam (Figure 10).
All the performed tests were stopped once reach the maximum displacement given by EN 594:2011 [27] equal to 100mm. At the end of the test the *only-timber* specimen did not show any failure because the high deformability of the structure given by the large displacements permitted by the ductile behaviour of the timber-timber screwed connections.

Figure 10: *The complete-wall system at the end the test*

Observing *complete-wall* specimens, both in case of monotonic and cyclic test, it was not possible to see any failure because the inner mortar layer was covered by the external panels. At the end of the tests, in order to identify possible local failures a visual analysis was performed removing a couple of panels: it was possible to recognize the cracks developed at the mortar-wood contact surfaces, see Figure 11.

Figure 11: *The specimens after the test: lateral panel removed in order to analyse mortar status*

The results of the experimental campaign were reported in Table 1 in terms of failure mode, stiffness k, maximum load F_{max} and corresponding displacement v_{max}. A comparison between load-displacement curves are reported in Figure 12.

Table 1: *Mechanical parameters of the tested specimens*

ID	wall-system	protocol	k [kN/mm]	F_{max} [kN]	v_{max} [mm]
1	only-timber	monotonic	0,3	21,6	96,6
2	timber-mortar	monotonic	5,9	82,7	87,8
3	timber-mortar	cyclic*	3,1	75,9	99,4

*mechanical parameters are referred to backbone curve of the first quadrant

Experimental results demonstrate, comparing the complete *wall-system* to the *only-timber* specimens, the high contribution to load-carry capacity (+400%) given by the infilled mortar; stiffness increases more than ten times. In particular, monotonic test on timber-mortar wall showed comparable strength and higher stiffness as the double-sheeted LFT, studied by Grossi et al [29,30], characterized by nails 2.8x60mm spaced at 50mm. Is noteworthy that LFTs showed high loss of strength, due to sheeting nail failure, in a range of top displacements between 40mm and 60mm. At the opposite the studied wall showed a continuous increase of strength until the end of the test (at an imposed displacement equal to 100mm).

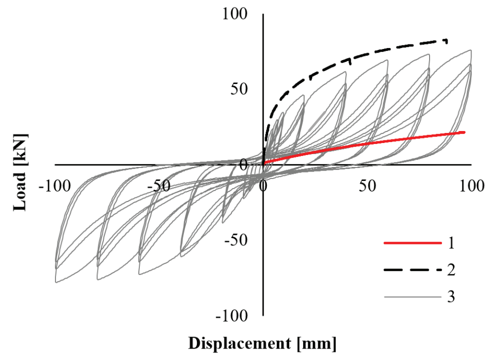

Figure 12: *Load-vs-displacement curves of monotonic and cyclic tests*

Figure 12 showed that the mortar infilled in timber-frame (complete *wall-system*) provided a not negligible contribution, in terms of strength and stiffness, associated with a good capacity of energy dissipation. These contributions are not considered in the design phase yet due to the lacking of a calculation method for *complete-system*. Nowadays practitioners design the timber-mortar walls as *only-timber* frame structure, consistent with EN1995:2004 [31] provisions and so, the contribution of the infilled mortar is neglected. The analytical calculation underestimates the strength, stiffness and energy dissipation capacity of the *complete-system;* hence further studies and tests are required in order to fully-characterize the mechanical properties of the presented constructive system.

5 CONCLUSIONS

This paper presents a new constructive system that uses timber frame structural walls infilled with lime mortar. Results of experimental campaign on a full scale shear walls are presented and discussed: the study considered both *only-timber* truss wall and timber-mortar walls. Monotonic and cyclic test were performed. Strength and stiffness showed by the complete timber-mortar wall are comparable with the mechanical properties of a typical LFT; furthermore an higher ductility was shown by timber-mortar walls. Timber-mortar constructions guarantee high comfort and quality of indoor living given by the use of only natural raw material, such as wood, lime, perlite and hemp. The presented constructive system can be considered as valuable alternative to traditional structural timber shear-wall for low-rising buildings.

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