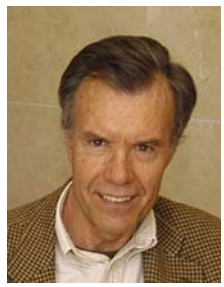
Rehabilitation of Lisbon's old "seismic resistant" timber framed buildings using innovative techniques.

Raquel PAULA
MSc in Structural Engineering (IST)
R&D Projects
Stap, SA
Rua Marquês de Fronteira, 8, 3.º dto, 1070-296 Lisbon
raquelpaula@gestip.pt

Training period in structural design. MSc thesis on confinement of RC columns with CFRP. Assistant in FCT-UNL and in LNEC. Some research work regarding fibre composites, restoration of timber and other rehabilitation techniques. Since 2003, is responsible for the R&D + Innovation Projects of Stap.

Vítor CÓIAS
Graduated in Civil Engineering (IST)
President
Grupo Stap, SA
Rua Marquês de Fronteira, 8, 3.º dto, 1070-296 Lisbon
vitorcoias@gestip.pt



Founder and president of a group of SMEs dedicated to structural rehabilitation, including of architectural heritage projects. Structural specialist of the Portuguese Engineers Society. President of GECORPA. Director of "Pedra & Cal" magazine. Invited lecturer in seminars and pos-graduation courses.

Summary

The historical downtown of Lisbon, also known as Baixa Pombalina, is relevant as urban and architectural heritage and therefore worth preserving. One of the most remarkable features of the buildings which make up this area is their structural concept, the distinctive gaiola system, which was used in the reconstruction of Lisbon after the devastating earthquake of 1755.

The gaiola was a standardized construction system which incorporated a set of features designed to provide the buildings with adequate seismic behaviour, enabling them to resist horizontal loads and to dissipate substantial amounts of energy.

As often as not this type of buildings requires interventions in respect of the original structure. New materials and techniques can be applied in innovative solutions to rehabilitate historic buildings by improving the global strength, ductility and energy dissipation capacity of the buildings whilst respecting their original structural concept and, therefore, their authenticity.

Keywords: rehabilitation, timber, beams, walls, connections, *gaiola*, FRP.

1. Introduction

Lisbon's "Baixa Pombalina", the historical downtown rebuilt after the disastrous 1755 earthquake, is composed of approximately sixty blocks, most of them rectangular and consisting in average of seven buildings.

Within each block, the buildings are constructed side by side, sharing the same gable walls. Some of the blocks have suffered, particularly after the onset of reinforced concrete, deep structural modifications, carried out in a piecemeal process, building by building. It is desirable (except for safety reasons) that no modifications are now allowed in the blocks which survived until the present day with the original Pombaline structure mostly unchanged. But it seems reasonable to admit, in the already modified blocks, that new alterations can be introduced using modern materials and

technologies, as a result of renovations sought by the owners, maintaining, at the same time, the existing architecture. Here "Pombaline" is the term coined after the Marquis of Pombal, the prime minister at the time of the 1755 earthquake, who took most of the decisions regarding the reconstruction of Lisbon [1].

"Baixa Pombalina", the historical downtown of Lisbon rebuilt after the great earthquake of 1755, is relevant as urban and architectural heritage and therefore worth preserving. One of the most remarkable features of the buildings which make up this area is their structural concept, the distinctive "gaiola" system, introduced after that earthquake (Figure 1).

This type of edifice requires, therefore, interventions in full respect of the original structural concept, presenting low intrusiveness and, whenever possible, reversibility. The rehabilitation methods used so far, resorting to current technologies and materials (cement and reinforced concrete), are not at all suited for this purpose [1].

Methods based on the use of advanced materials and new techniques seem much more suitable. Some research work which has been carried out is briefly described, regarding particularly the strengthening of the original "gaiola" framework and its connections to the main masonry walls. The inherent low intrusiveness is underlined, which will enable structural rehabilitation interventions to be carried out "surgically", with only tolerable disruption of the buildings, either in terms of their users or in terms of their structural system.

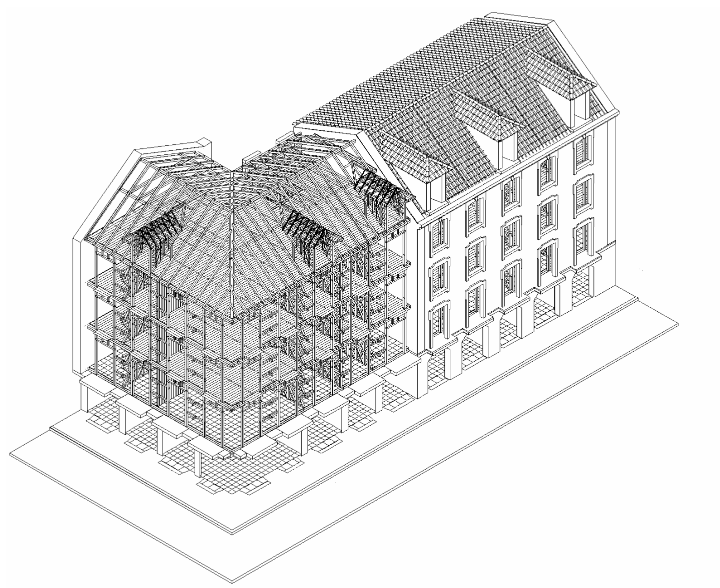


Fig. 1 Part of a Pombaline block. Building with the façade walls removed to show the timber bracing system.

2. Characterisation of the "Baixa Pombalina"

2.1 The Pombaline buildings

In line with the post earthquake measures designed by the chief engineer, Manuel da Maia, the new buildings during the first decades of reconstruction after the big shake incorporated a set of features intended to provide them with adequate seismic behaviour, enabling them to resist horizontal loads and to dissipate substantial amounts of energy. Among these measures, the so-called "gaiola" or "cage" system stands out.

The system consists of a set of timber members embedded along the inner face of the main stone masonry façade walls (Figure 2). To these members and to the ashlars around the openings, an internal timber grid is connected by means of iron cross ties. Further bracing is provided by the

timber floors, whose diaphragm action is enhanced by iron ties, bolted to the floor beams and deeply embedded in masonry main walls, and by timber connectors, named "hands", nailed to the above mentioned timber grid and also embedded in the masonry. The confined facade pilasters are then connected to a two-directional vertical bracing system of timber framed walls with light ceramic and rubble masonry infill. The "gaiola" designation was coined because the building seemed like a big cage, with the carpentry work high up in the air [1].

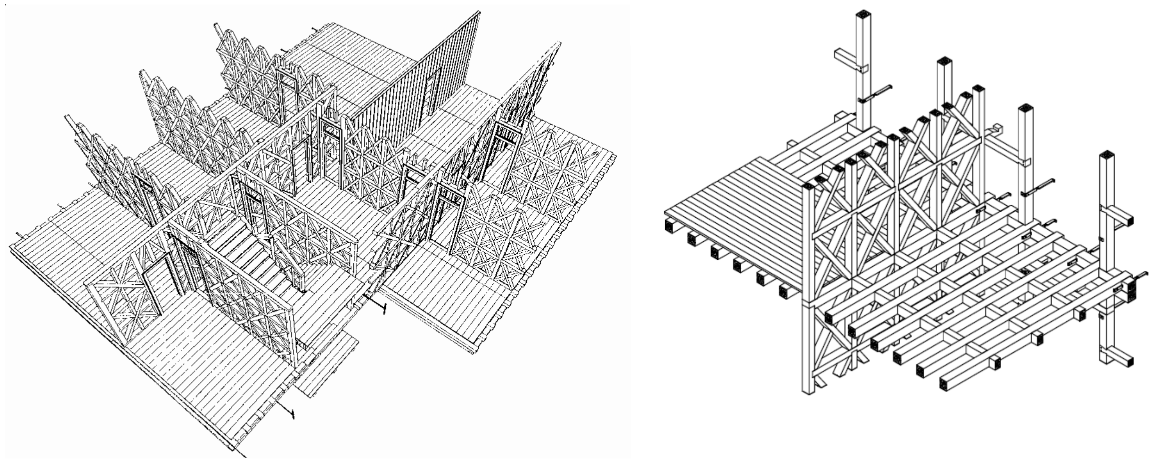


Fig. 2 Details of the Pombaline construction. Internal timber frame. Load bearing composite wood-masonry walls. Wooden floor slabs. Structural elements of floor slabs. Floor coverings.

The "gaiola" system is considered an innovation of the Pombaline city planning, adopted when it was found out that, due to complicated property expropriation and reassignment, the buildings needed to have four floors instead of two, as was Manuel da Maia's initial idea and was the case at Vila Real de Santo António, in the Algarve. It is said that the building concept was implemented by one of the architects, Carlos Mardel, after a load test on a large scale model in the main downtown square, using units of soldiers to generate the dynamic actions. But, presently, it is assumed that most of the constructive details of the new structural system were produced by the master draughtsmen of Casa do Risco (Draughtsmen House), used to the design of timber structures for ships. These details were probably handed down to the building carpenters orally or by means of drawings and sketches and were soon lost. They gave rise, meanwhile, to a "know-how" that lasted, in spite of suffering substantial degradation, until the first quarter of the 20th century, when the last "gaioleiros" (buildings using the system) disappeared [1].

Notwithstanding the many references to a possible code, regulating design, establishing member sizes, connection details and constructive procedures, no document has been found specifying the "gaiola" construction or establishing its mandatory character. The first modern Portuguese seismic code, dated from 1958, starts with a reference to "the code published after the earthquake of 1755" but, unfortunately, it seems that such a code never existed in writing. In fact, the earthquake of 1783, in Calabria, Italy, appears often in specialized literature as having given rise to the first rules for seismic construction, namely, the adoption of timber framed walls with mortared stone infill, instead of rubble. However, the concept seems to have been inspired on the Pombaline constructional system [1].

Records on the original design of the Pombaline buildings seem not to be available. In the city council archives, only documents pertaining to the successive modifications requested by the owners are available. But the buildings of the historical downtown are grouped in rectangular blocks, measuring in plan around 70 × 25 m2, with a narrow central yard measuring 45 × 2 m2. The buildings had originally five floors, including ground floor and attic and the height of the façade was approximately equal to the width of the main streets, being constant for all the buildings. Each block has stone masonry walls in the external walls and in the internal walls facing the central yard. These walls are around 0.9 m thick at the ground level, with a slight reduction in the upper floors. The main walls are connected transversally at ground level by other masonry walls, 0.5 m thick.

Some of these walls are continuously extended further up above the roof, separating the different ownership and acting as fire walls. The structure of the first floor is generally made up of stone masonry arches and vaults. From the first floor up, the pilasters of the exterior walls, both in the façade and in the back yard are strengthened as detailed above [1].

Several basic configurations of timber-masonry load-bearing walls have been identified in the old Lisbon buildings (Figure 3). Timber species used in these buildings and their cross-section dimensions also presented some variation. The empty spaces of the walls were filled with rubble masonry made of small stones and ceramic elements recovered from the ruins of the earthquake, assembled with lime mortar [2].

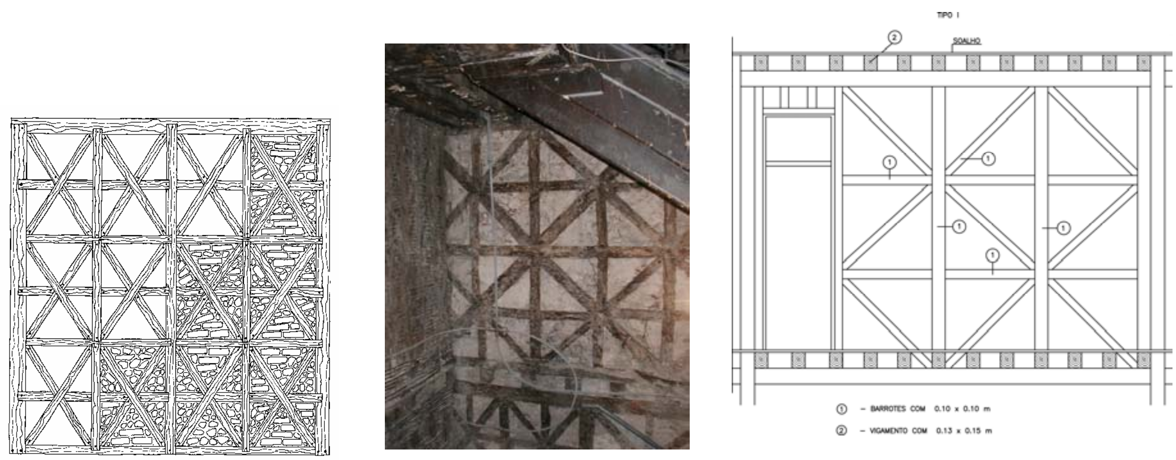


Fig. 3 Examples of different configurations of timber-masonry walls.

An example of a representative wooden roof structure is illustrated in Figure 4. The rigid structure that supports the roof consists of a set of king post trusses. Jointed timber elements form the triangular frame. The king post is the central vertical timber. Roof structures also include the secondary elements underneath the roof coverings.

The foundations rest generally on a timber grid laid on short timber piles, intended only to stiffen the alluvial soil and to create a good working platform at the ground water level. In many places where the new buildings are laid out on the remains of pre-earthquake buildings (street slabs, footings, masonry blocks), these older constructions were used as foundations.

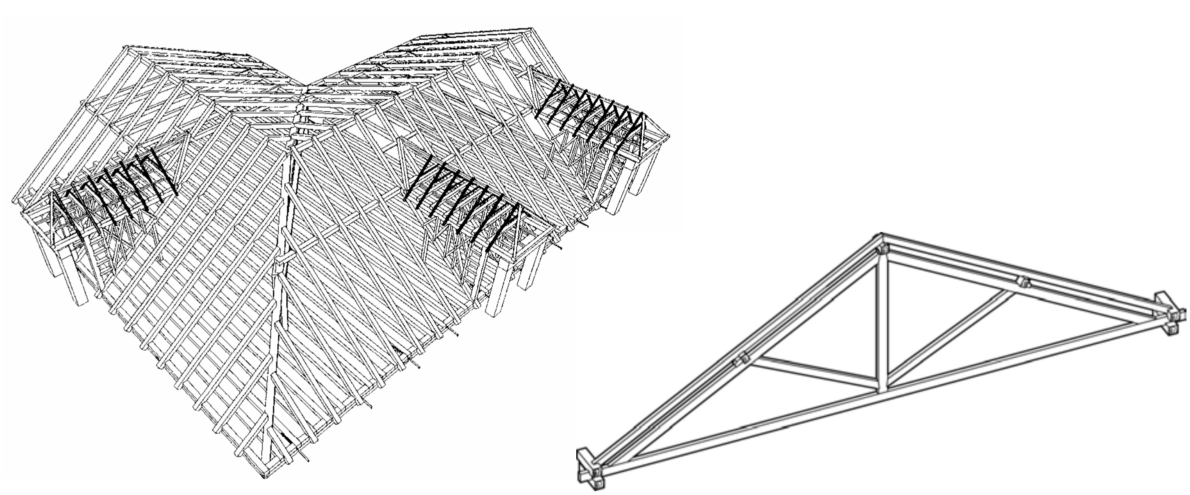


Fig. 4 Details of the Pombaline construction: (a) roof structure, b) king post truss.

2.2 Vulnerability and deterioration of timber structural elements

Buildings in "Baixa Pombalina" have undergone successive and occasional modifications until quite recently. Main changes have been the construction of extra floors, inadequate widening of existing façade openings and removal of walls and pillars, notably on the ground floor, and addition of steel and reinforced concrete elements [1].

The introduction of new materials, with mechanical behaviour considerably different from the original ones, resulted in uncontrolled changes in the original structural system, possibly decreasing its strength and capacity to dissipate the energy associated with seismic actions [2].

Overloading and modifications on the buildings, on the one hand, environmental effects, insect damage, mould, and biological damage (rot), on the other hand, can severely compromise the integrity and performance of wood structures. Decayed zones, significant reduction of section and excess of deformation are the most frequent anomalies that have been detected on the timber elements (Figure 5).

Many structures are in need of some kind of rehabilitation due to the deterioration they have undergone with time. The rehabilitation methods used so far, resorting to current technologies based on the intensive use of cement and reinforced concrete, due to their strong invasive character, are not at all suitable in the case of the "Baixa Pombalina", given its the historical and architectural value.

Current repair methods are often intrusive and lead to the waste of good material. Therefore, there is room for low-invasive strengthening solutions, of "surgical" nature, that will simplify interventions, involving tolerable disturbance for the users of the buildings.

a)

b)

Fig. 5 Deterioration of timber floor beams in Lisbon's downtown: (a) decayed beam end, (b) reduction of cross section in middle span.

3. Innovative solutions to improve the structural behaviour

New materials and techniques can play an important role in the rehabilitation of the "Pombaline" buildings compound, by improving the structural behaviour of: the original timber floors, the connections between the timber floors and masonry walls, the original timber braced walls, and the connections between the timber framed walls and the main masonry walls.

Together, these improvement solutions are capable of enhancing the global strength, ductility and energy dissipation capacity of the buildings whilst respecting their original structural concept and, therefore, their authenticity. In particular, the interventions need to have minimum environmental impact both on the existing use of the building and on the appearance of the structure.

Maintenance and conservation of built heritage frequently involves rehabilitation and consolidation of certain components or parts of the existing timber elements. While in some cases, the substitution of the original timber is inevitable, in other situations, to preserve the original materials and

structure or even for economic reasons, it is better to adopt a local renovation of the decayed parts as well as the reinforcement of the existing structural elements.

Innovative solutions are capable of providing the necessary strength and durability to realize a long-term service life for wood structures. Most of the new solutions can be optimised by the use of non-traditional materials like epoxy resins and advanced Fibre Reinforced Polymer composites (FRP).

3.1 FRP reinforcement

FRP composites combining high resistance fibres (glass, aramid or carbon fibres) and a polymeric matrix (epoxy, polyester or vinylester resin) have a wide variety of industrial applications. The widespread use of FRP composites in the aerospace and defence related sectors, sporting goods industry, etc, has given rise to their application in the civil engineering sector and are currently viewed as highly promising materials in the construction industry.

Key advantages of FRP are high strength/weight and stiffness/weight ratios, which significantly exceed those of conventional civil engineering materials, free-form and tailored design characteristics, ease of handling and versatility, corrosion and fatigue resistance and a high degree of inertness to chemical and environmental factors [3].

The growing use of FRP in repair and retrofit of concrete and masonry structures has opened the door for similar applications in wood. FRP materials have been used successfully to strengthen existing concrete columns for higher seismic loads, as well as concrete and masonry walls that lacked adequate steel reinforcement. The versatility and ease of installation make FRP retrofit solutions extremely effective [4].

New materials can be applied in innovative solutions to improve the seismic behaviour of old buildings. Unlike traditional methods, the new approach is reversible. It is a less disruptive process, and can be implemented without the need for foundation reinforcement because the materials are so lightweight.

Composite materials for civil engineering are available mainly in the form of:

- thin unidirectional strips and plates (laminates);
- flexible sheets or fabrics, made of fibres in one or at least two different directions, respectively;
- profiles and rods.

Epoxy adhesives include a wide variety of products with quite different properties in terms of adherence to timber, viscosity, reaction and setting time, creep, strength and elasticity, therefore suitable formulations should be identified for each job. Despite some less good qualities, epoxy adhesives are in general terms the most suitable for in-situ repair operations, since they do not require high pressure during their application and curing and they can be reasonably tolerant to glue line thickness variation [1].

FRP rods and plates have a particularly effective application for the local reinforcement of structural timber joints. These materials are also commonly used in structural repair operations, either being inserted in critical cross-sections, or used for load transmission when damaged beam ends are cut off and replaced with new timber or epoxy mortar.

FRP composites can be embedded in existing wooden beams and joints to provide a "hidden" strengthening solution. The system can be designed to increase the strength of beams deficient in flexure and/or shear. End connection details can also be incorporated to assist in load transfer between elements [5]. FRP techniques should only be applied by certified applicators using certified equipment.

3.2 Low intrusion restoration techniques for timber structures

Low intrusion restoration techniques using structural adhesives and FRP are suitable for repairing and strengthening existing timber structures and represent significant improvements in current practice in conservation strategies for timber. The option for advanced materials aims at providing systems with such features as low mass, ease and speed of installation with minimum personnel and plant requirements, versatility and structural efficiency. In combination with traditional carpentry methods, versatile timber restoration solutions lead to less waste of original good material, reduced

visual impact and an aesthetically pleasing appearance [6, 7].

Licons - Low intrusion conservation systems for timber structures [8] - European project addressed the development and validation of these innovative techniques as well as the establishment of a quality assurance methodology for executing each type of repair, based on the experimental trials. The systems are intended to reduce disturbance and eliminate the waste that is often associated with fully in situ methods, thus achieving better construction and large overall project cost savings.

Main configurations include: modified flitch and upgrade of beams (Figure 6); beam reinforcement, including above decorative ceilings (Figures 7 and 8); beam end repair (Figures 9 and 10); upgrading of glulam beams; king post truss consolidation and bonded-in joints.

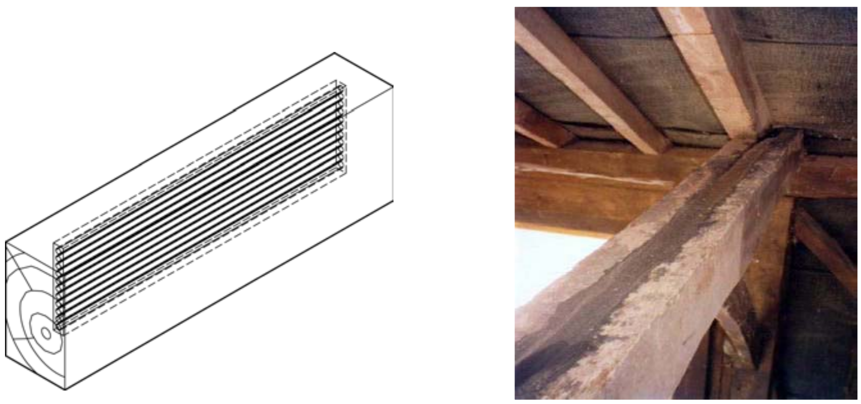
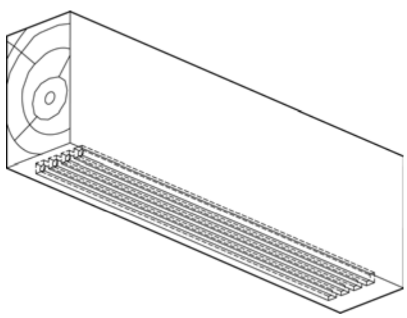
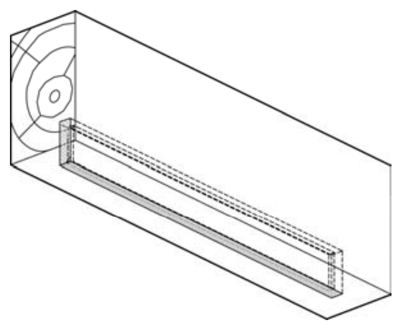


Fig. 6 Modified flitch and upgrade of beams

a)



a)



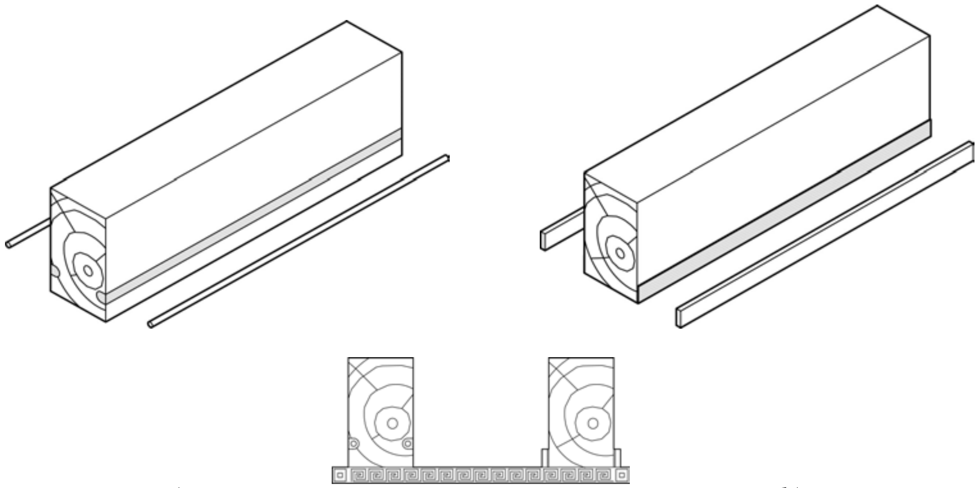
b)

Fig. 7 Beam upgrades using: a) bonded-in rods and b) bonded-in laminate.

The basic components of the technology are the adhesives, strengthening rods or plates, and prefabricated timber components, if necessary. The primary restoration material is the original timber component that is identified during the inspection with regard to species, age, current condition, i.e., moisture and visual grading.

The restoration components are introduced to the site, forming an integral part of the repaired structure. They may be one of or a combination of the following:

- prefabricated timber component of the same species and moisture as the original timber, usually to replace a portion of a component;
- single or multiple configuration of metallic or FRP rods or plates as overall strengthening components or as shear connectors.



a) b)

Fig. 8 Beam upgrade above decorative ceiling using: a) bonded-in rods; b) externally bonded laminates.

Adhesives are usually a two or three part epoxy system which is used as the interface between the original timber and the rods or plates. The adhesives should be specifically formulated for timber engineering, to be used in crack injection, fixing of anchorages in timber, filling of drilled holes and slots to fix metallic or FRP rods or plates.

After curing, mechanical properties of the adhesives should be compatible with those of timber. Timber should have a moisture content not exceeding 20%. The adhesive should have low surface tension in order to obtain a good spreading of the material.

The rods and plates can be metallic or of FRP materials, always in accordance with the design. The metallic reinforcement elements can be of stainless or steel adequately protected against corrosion. The metallic rods should be threaded or ribbed bars. The FRP rods or laminates may have some diverse compositions, for example, unidirectional glass or carbon fibres agglutinated on a matrix of epoxy resin; unidirectional glass fibres on a polyurethane thermoplastic matrix, etc [9].

If a beam has some rot in the centre, which makes it inadequate, or it is required to increase the bending capacity, then an epoxy may be used to bond steel or FRP rods into a slot cut along the centre of the beam from above (Figure 6). The reinforcement can either be in the form of bars or a vertical laminate. Individual rods are easier to handle and will adapt to the line of the beam, but a higher section modulus can be achieved with a laminate [10].

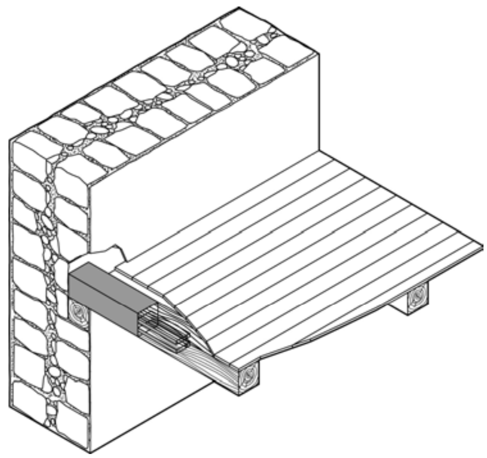
Beam ends can be repaired by drilling holes in the sound material after the decayed end has been removed. Resin is injected into the holes and the decayed part is replaced by a timber prefabricated component (Figures 9 and 10).

The prefabricated timber components should be of the same species of the timber to be repaired, or compatible, in terms of its mechanical properties, durability and colour. However, if the durability of the original timber is rather insufficient regarding the particular hazard class, timber with adequate natural durability or with a selected preservative treatment may be used [11].

Case study presented in Figure 10 consisted of pine floor beams, with significant end decay, thus needed to be repaired. Due to the presence of the existing wooden floor, the top surface of the beams was not accessible. The repair technology was chosen for both on-site accessibility requirements (impossible to work from top) and cost analysis. The intervention was completely carried out from below the beams [12].

Instead of being installed in situ in the sound timber, the reinforcement elements can be pre-inserted in the prefabricated components at the workshop. The option for the best configuration depends, for example, on the constraints of accessibility and available space to place the prefabricated components.

Licons techniques permit the rehabilitation and consolidation of timber structural elements without extra weight and total removal of the sound timber, facilitating significant cost savings and with little disruption to the space below.



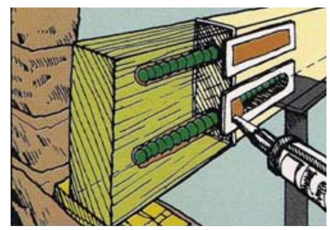


Fig. 9 Beam end repair using a prefabricated timber component with pre bonded-in rods. Encase of rods in lateral slots in sound timber. Injection of resin.

a)

b)

Fig. 10 Beam end repair using prefabricated timber components: a) injection of epoxy resin into the holes in the sound timber; b) injection of top slot.

3.3 Improving the connections between the timber floors and masonry

The devices that were used to connect timber floors structure to the resistant masonry walls, when existing they are usually deteriorated, thus no longer suitable to assure the connection.

Improving the connections between the timber floors and masonry walls not only increases the resistance of the structure of the floors but also the global behaviour of the structure of the whole building, particularly in what concerns the seismic action, because of the contribution of the timber floors to the structural stability [13].

Low intrusive and removable connectors are shown in Figures 11 and 12. The bars are inserted into

the thickness of the walls and are anchored on the wall and on the timber beams by special devices. There are different types of connection devices either to be installed in the longitudinal or in the transversal direction of the beams.

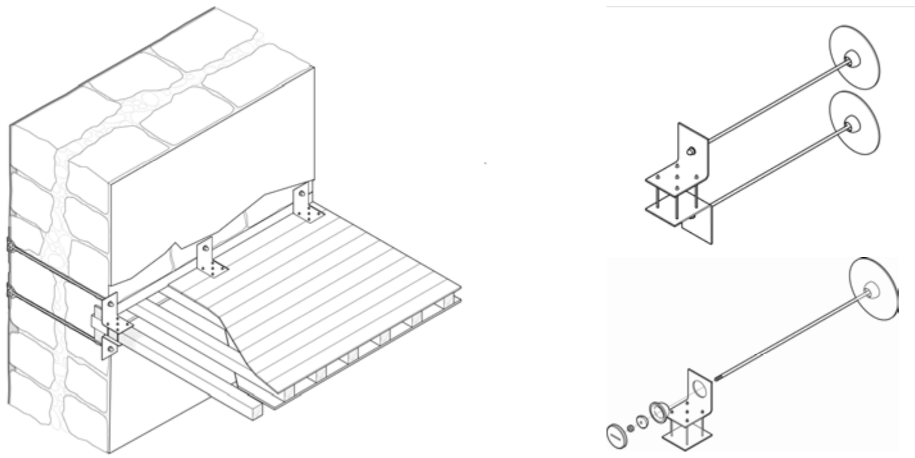


Fig. 11 Connection devices between timber floors and masonry. Longitudinal direction.

In the longitudinal direction, the L-shape plates are connected to the beams usually with threaded bolts. In the transversal direction, the plates are bonded to the pavement. In order to assure the adhesion, a layer of glass fabric and epoxy resin composite may be put between the beam and the plate.

As the execution of aligned holes in the thickness of the walls is difficult to assure, the devices have a special anchoring semi-spherical rótula (ball joint) that enables the fitting of important misaligning holes. In order to reduce the visual impact of the anchoring, the semi-spherical rótula and the nut are lodged in a semi-spherical cup with a lid. The set of pieces can be hidden in a small concavity on the wall and then rendered.

Instead of inserting the bars through the whole thickness of the masonry walls, sock type anchors may be used (Figure 13).

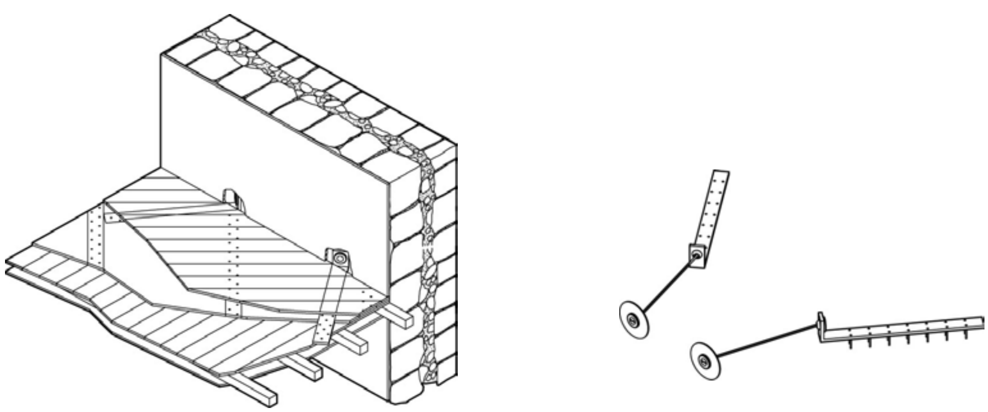


Fig. 12 Connection devices between timber floors and masonry.

3.4 Strengthening of the original timber braced walls

The contribution of the structural capacity of the timber framed walls with light ceramic and rubble masonry infill, to the global lateral stability of the buildings is easily understood by current structural engineering. Of course the structural capacity is dependent on diverse factors, like the condition of the materials and the connections between the different elements [13].

After a very careful inspection, it may be concluded that it is necessary to remove some parts of the timber frame, followed by its substitution with new timber. The new timber parts should be connected to the remaining sound timber by means of metallic plates and screws or using the low invasive methods already described.

Also, externally bonded GFRP fabric may be used as presented in Figure 13. In order to assess the effects of FRP solutions to strength timber load-bearing walls, several tests have been carried out [14]. Full scale models of an individual unit of a typical timber frame wall panel were produced and tested in diagonal compression close to complete failure. After testing, the distorted test panels were brought back to their initial configuration, strengthened and subjected to diagonal compression again.

Every test panel was strengthened by repairing both outer timber members of the frame on the shortest sides of the panel. This was done by opening one slot in the broken timber member and placing in it one 10mm diameter glass fibre reinforced polymer (GFRP) rod glued with epoxy adhesive. Each GFRP rod was positioned the nearest possible to the centre of the corresponding member cross section, in order to avoid non-symmetrical strengthening effect. Two rods were therefore used for each panel.

In addition to the reinforcing rods, glass fibre fabric stripes were glued to the joints where tension conducted to the separation of timber elements during previous testing. This was done on both faces, after the above-mentioned slot had been filled with epoxy adhesive and this left to cure. The glass stripes were as wide as the timber member they were glued to, and 25cm long; in the case of extreme joints, glass fibre fabric stripes were therefore folded around the edge of the panel.

The strengthened wall panels have presented a very reasonable recovery of strength (between 73% and 127% of the strength of the initial panel) and a very good improvement in their ductility (between 158% and 316% of the maximum diagonal deformation withstood in the first test).

3.5 Improving the connections between the timber framed walls and the main masonry walls

The internal timber grid of the original structure of the buildings in "Baixa Pombalina" was connected to the main stone masonry façade walls and to the ashlars around the openings by means of iron cross ties. One of the main deteriorations of these connections is due to the corrosion of the ties, which are no longer suitable to assure the connection.

The fundamental interventions in this kind of walls are thus related to the reestablishment and even the reinforcement of the connection conditions. This can be achieved by means of the installation of a set of low intrusive and removable connectors as shown in Figure 13. Similarly to the previously presented devices that improve the connections between the timber beams and the masonry, the reinforcing bars are inserted into the thickness of the main masonry walls and are anchored on the timber framed wall by special devices.

The L-shape plates are connected to timber with threaded bolts. Preferably, a GFRP fabric may be put between the timber and the plate. The anchoring devices may be the semi-spherical ones that have been previously shown in Figure 11. Also in this case, instead of inserting the rods through the whole thickness of the masonry walls, sock type anchors may be used as shown in Figure 13.

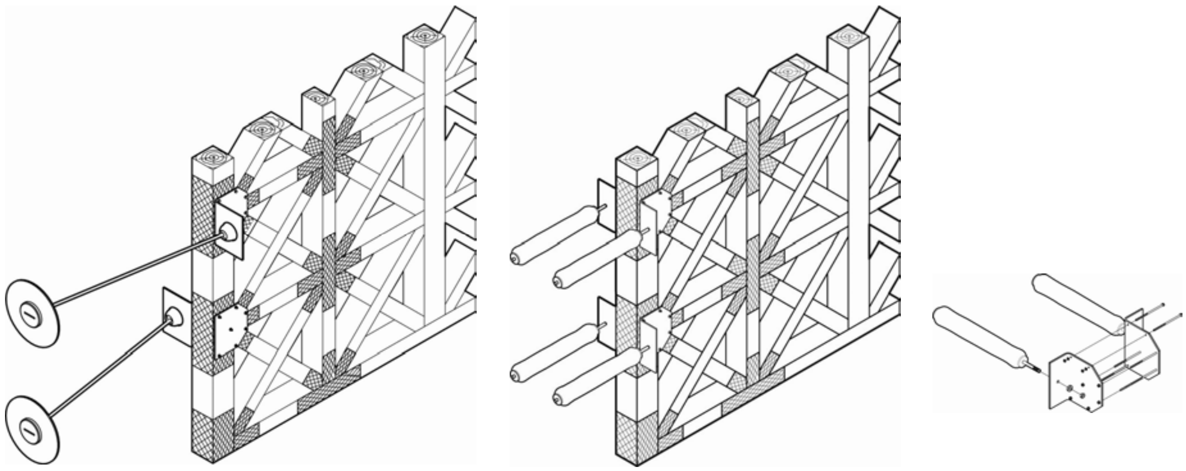


Fig. 13 Timber braced wall strengthened with externally bonded GFRP fabric and connection devices to the main masonry walls.

3.6 Conclusions

The historical downtown of Lisbon, also known as "Baixa Pombalina", comprises the most complete collection of the seismic resistant building technology, the gaiola system, which was used in the reconstruction of Lisbon after the devastating earthquake of 1755. The gaiola was a standardized construction system which incorporated a number of innovative methods designed to resist seismic forces. The system consists of a set of timber members embedded along the inner face of the main stone masonry façade walls.

Innovative techniques can play an important role in the rehabilitation of the buildings in the Pombaline downtown. Whilst respecting the original structure concept and, therefore, their authenticity, these techniques are capable of improving the global strength, ductility and energy dissipation capacity of the buildings.

Maintenance and conservation of built heritage frequently involves rehabilitation and consolidation of certain components or parts of the existing timber elements. In this paper, a brief description of non-traditional materials and rehabilitation methods, which are capable of providing the necessary strength and durability to realize a long-term service life for timber structures is presented.

3.7 References

[1] Cóias e Silva, Vítor, "Using advanced composites to retrofit Lisbon's old "seismic resistant" timber framed buildings", *European Timber Buildings as an expression of Technological and Technical Cultures*, Éditions Elsevier, 2002.

[2] Ramos L., Lourenço P., "Seismic analysis of a heritage building compound in the old town of Lisbon", International Conference 250th Anniversary of the 1755 Lisbon Earthquake, 1 to 4 November 2005, Lisbon, pp. 362-368.

[3] *Externally bonded FRP reinforcement for RC structures*, Technical report, fib Bulletin 14, CEB-FIP, July 2001.

[4] M. Ehsani, M. Larsen, and N. Palmer, "Strengthening of Old Wood with New Technology, FRP Laminates and Epoxy Help Support New Loads in an Existing Wooden Gymnasium", STRUCTURE magazine, February 2004, pp. 19-20.

[5] Tyfo Systems for Wood Using Glass, Aramid, and Carbon Fiber Reinforced Tyfo® Materials combined with our Tyfo® Epoxy Matrices, Fyfe Co. LLC, 2003.

[6] Cruz H., Custódio J., Execução e Controlo de Qualidade da Reparação de Estruturas de Madeira com Colas Epoxídicas e FRPs, CIMAD 2004, pp.569-578.

[7] Paula R., Cóias V., Cruz H., "Sistema pouco intrusivo de reabilitação de madeira", *Revista*

Pedra & Cal, Ano VII, N.º 29, Jan.-Mar. 2006.

[8] www.licons.org

[9] Resiwood system timber engineering product data, Rotafix Ltd.

[10] Ross P., *Appraisal and repair of timber structures*, Thomas Telford Ltd, London, 2002.

[11] EN 1995-1-1:2004: Design of timber structures. Part 1-1: General - Common rules and rules for buildings.

[12] Paula R., Cruz H., "Reabilitação pouco intrusiva de vigas de madeira. Um caso de estudo", *PATORREB 2006 – 2.º Encontro sobre Patologia e Reabilitação de Edifícios*, 20-21 Março 2006, Faculdade de Engenharia da Universidade do Porto, Departamento de Engenharia Civil.

[13] Appleton, João, *Reabilitação de Edifícios Antigos*, Edições Orion, 1.ªEdição, Setembro de 2003.

[14] Cruz H., et al., "The use of FRP in the strengthening of timber-reinforced masonry load-bearing walls", LNEC, 2001.