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# Portuguese traditional timber structures: Survey, analysis and strengthening

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ABSTRACT: This paper aims to present an overview on the Portuguese traditional timber structures pointing out the current approach on their refurbishment. The results of an extensive survey intending to assess geometries, materials, and on site pathologies are presented. The most common traditional timber structures are analyzed, the degradation processes are reported and the main strengthening needs are discussed.

## 1 INTRODUCTION

Traditional building construction in Portugal (from the 18th to early 20th century) adopted timber roof and floor structures and, in some cases, also timber reinforced masonry walls. A significant number of these buildings are still in use, despite some major modifications. Even when the use of concrete became generalised, timber structures kept an important use, in particular, in slab and roof construction.

Actually, a considerable number of timber structures require structural intervention in consequence of natural degradation of the material (ageing), improper maintenance, faulty design and/or construction, lack of reasonable care in handling of wood and/or accidental actions.

Traditional timber structures should be carefully analyzed – with the same level of detail that structures of others materials are studied. Because of their significance and constant presence in construction, the importance of the correct analysis of traditional timber construction should not be neglected, with the risk that, with the possible misunderstanding of their behavior, in few years, they can disappear. Designers must be aware of the material properties and must feel comfortable in the interpretation of the structural system performance. The misunderstanding of the global behavior of traditional timber structures can result in unacceptable stress distribution in the members as result of inappropriate strengthening interventions (in particular, when connections are strengthened).

## 2 ROOF STRUCTURES

Several timber roofs structures were surveyed (Branco, 2008) in order to collected common values and ranges of geometry, connections solutions, wood species and load parameters. A considerable number of buildings were visited from which more than thirty timber trusses were assessed. The survey confirmed the importance of King-post and Howe trusses configurations in Portuguese timber roofs construction. The span defines the truss configuration used. Therefore, King-post trusses are the most popular due to the common small value of span, below 7 meters, although, even for higher span values, this configuration is, wrongly, employed. For spans over 10 meters, the Howe truss is the most common configuration used, in particular, in the form of Princess-truss.

The distance between the axes trusses is normally in the range of 3 to 4 meters, with a common value of 3,5 m. The trusses are composed by slender timber elements, 7–10 cm of width by 10–12 cm height for posts and struts and, 18–25 cm in the case of rafters and tie beams. The wood species more frequent are: Maritime Pine (*Pinus pinaster*, Ait.), Eucalyptus (*Eucalyptus globulus*, Labill.) and Chestnut (*Castanea sativa*, Mill.).

Single or double steps, presenting in some cases tenon and mortise, make the joints between truss members. The range values for the geometry characteristics of the steps have significant variation. For example, the rafter-tie beam connection is commonly made using a single step however the notch geometry is not precise.

Connections are usually strengthened with metal elements. While nails are extensive to all connections, binding strip and straps are common in the connections with the tie beam and stirrups are frequent in rafter-tie beam and king post-rafters connections.

Improper maintenance of the structure and faulty design or construction are the main causes of safety reduction of Portuguese timber trusses. Problems associated with moisture contents, especially near the supports, are usually present. The faulty design is frequently consequence of a wrong selection of the truss configuration for the roof span (Fig. 1) and due to eccentricities in the purlins.

In fact, although, a strong emphasis is traditionally placed on the need to limit bending moments in the truss elements, eccentricities in the purlins are common (Fig. 2).

Figure 1. Incorrect truss configuration for the roof span.

Figure 2. Wrong positioning of the purlins with eccentricity relatively to the truss joint.

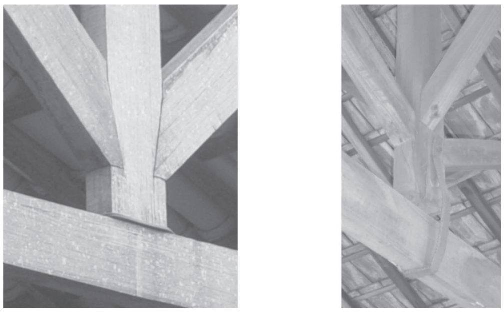


Figure 3. Examples of misconceived connections between the king post: and the tie beam.

Despite being less significant, eccentricities of the supports to the tie beam-rafter connection are common. When important eccentricity exists it is normal to introduce braces. A major source of uncertainty in the global structural behavior of traditional trusses, in particular in the case of the king post configuration, is related to the connection between the king post and the tie beam. Although traditional construction manuals suggest the disconnection between the post and the tie beam, in practice, examples of misconceived connections are not uncommon (Fig. 3).

### 2.1 *Truss static behavior*

Traditional Portuguese trusses are subjected, essentially, to normal stresses associated with axial forces and bending moments induced by the self-weight and asymmetric loads (as the ones produced by snow and earthquakes). The elements with higher stresses are the rafters. The tie beam and struts have only significant normal stress and the posts only shows tension stresses. In a plane structure, like traditional timber trusses, submitted to concentrated loads on the joints, without bending of the members, stress distribution in the structure results directly from its geometry. However, this behavior can be easily modified if the static model is changed. Assessment of constructed timber trusses shows various differences on their structural model. In fact, despite construction recommendations, intuitively developed over centuries by carpenters, it is common to find examples where they were not taken into account. After an evaluation of the variations in the truss behavior that can be achieve as result of the model assumed in the design (Branco et al., 2006), it is suggested:

1. The application of concentrated loads out of the joints, for example originated by a wrong positioning of the purlins, can compromise the structural global safety;
2. The eccentricity of the supports, relatively to the tie beam-rafter connection must be minimizing. It is recommended that the reaction force pass by the intersection point of the tie beam and rafter axis;
3. The tie beam must be suspended to the posts. Iron strap shall be used, nailing it only in the post, suspending the tie beam with a connection without bending stiffness and preventing out-of-plane deformations;
4. When the tie beam-post connection is rigid, the natural frequencies and modal shapes of the truss are clearly modified;
5. For non-symmetric loads, *e.g.* snow, earthquakes and wind, the influence of the joint stiffness became relevant;
6. The performance of the tie beam-rafter connection is crucial, not only in consequence of the high level of stresses concentrated there but also because they represent zones where biological deterioration is more frequent;
7. The supports must be able to resist horizontal movements. Friction forces are insufficient to resist do horizontal movements caused by earthquakes.

Although the importance of these observations and recommendations, the key for an adequate structural behavior is the selection of the adequate truss configuration. Indeed, traditional Portuguese timber trusses were think to behave as plane structure submitted to point loads on the joints causing essentially axial stresses in the members. When the number of posts is less than the total of purlins, the structural safety is severely reduced. In this case rafters are subjected to bending moments despite be slender. As a practical rule, the truss configuration must have a number of posts equal to total of purlins used to support the covering structure.

### 2.2 *Degradation and strengthening*

The most common degradation processes in timber roofs structures can be divided in three families. The

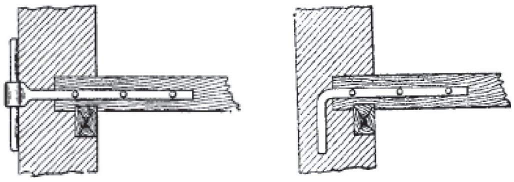
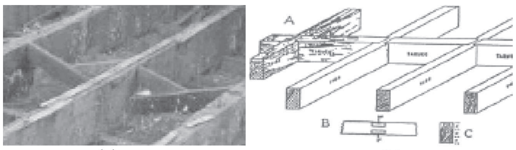


Figure 6. Examples of metal devices use to ensure the connection between the main beams and the masonry wall (Segurado, 1942).




(a) (b)

Figure 7. Examples of floor strutting. (a) Herring-bone and (b) Solid.

40 cm, to ensure the adequate ventilation of the wood. Because the renovation of the air must be constant, ventilators must be placed in the masonry walls.

### 3.1 *Damages and strengthening needs*

Damage in timber slabs can have different sources: a) natural defects of wood; b) biological degradation; c) atmospheric agents in particular, transient moisture content; and d) design, execution and maintenance errors. Despite the presence of structural damage in timber slabs, it is unusual to observe a failure on these structures. This can explain by the system effect given by the floor boards and by the high safety level normally applied in the past in the design of those structures. The true is that, even in the presence of severe damages, the strengthening of ancient timber slabs is possible. In general, strengthening intervention on timber slabs involves the ends beams near the supports – they are the more exposed zones to biological and atmospheric agents, local reinforcement of the main beams as consequence of local damages and the introduction of additional structural elements to increase the load-carrying and to reduce vertical deformation.

The supports of the main beams can be strengthened with the introduction of wall plates and/or corbels made of wood or steel, or, when the damage is severe, the ends beams can be substitute by a new timber pieces connected to the existing beam by steel or fiber reinforced polymers bars glued. In some cases, the ends beams are totally reconstructed through the injection of fluid adhesives.

Normally steel plates or wood based boards are nailed or screwed to the main beams when those elements need to be strengthened. When the load-carrying capacity of the slabs has to be increase, or the vertical deformation of the slab is significantly high, it is current to introduce additional elements to the slab structure. In most of the cases, those new elements are made of wood or wood based elements and steel. In these cases, additional elements are introduced between the main beams (placed parallel to them) or are placed perpendicular to the main beams with the aim to reduce their span. In this last case, the new element presents significant cross section as result of the considerable load that they support.

In Portugal, a strengthening technique that has become popular is the transformation of the timber slabs in composite timber-concrete solutions. However, a lack of information has result in several misconceived applications. Concrete simply placed over the timber slab (Ramos & Lourenço, 2004), connectors extremely stiff and expensive became generalized.

## 4 TIMBER WALLS

Following the big earthquake that destroyed large areas of Lisbon in 1755, and the empirical knowledge collected from the buildings which survived this earthquake, a structural solution, generally referred to as "construção pombalina", was imposed, in order to speed up reconstruction and to guarantee the required seismic resistance of the buildings.

The basis of this building system was the three-dimensional timber structure, called "gaiola" (birds cage), that was totally built up to the roof prior to in-filling the wall frames with the "masonry" (small stones, brick and mortar), that would subsequently wrap up the timber elements. In some cases, exterior masonry walls (as thick as 90cm at the basis) would enclose timber elements to which the floors and the orthogonal load-bearing walls from gaiola were connected (timber-to-timber); in other cases the exterior masonry walls would lay against the gaiola and be connected to it through short timber pieces (mãos) or steel elements (esquadros) bearing in the masonry (Cruz et al., 2001).

Some similar examples, using the same timber frame techniques can be found at Guimarães. In fact, the well preserved timber frame buildings have contributed for the title of World Heritage given recently to its historic city center.

Two types of timber walls can be found in Portuguese buildings: light-framed timber partition walls (tabique walls) and timber reinforced masonry walls (frontal walls) (Fig. 8).

In the case of these timber frame walls, most frequent damage is related to timber decay or to its destruction by subterranean termites resulting from high moisture content attained in the timber for sufficiently long periods. This biological degradation frequently spreads from the timber pieces that are encased or adjacent to exterior walls, or located near windows or balconies, directly under the influence of defective roofs, or even in the area of ad-posteriori fitted-in facilities (kitchens, washing, and toilets). As a consequence of this, suitable repair of major timber elements is often needed. Their in situ strengthening may be then the preferable solution, especially where

(a) (b)

Figure 8. Examples of Portuguese traditional timber walls. (a) Tabique walls and (b) Frontal walls.

the affected member also supports timber floor or roof beams.

Only limited research was found on the experimental assessment of traditional Portuguese timber walls. Timber reinforced masonry walls (frontal walls) retrieved from an 18th century Lisbon building were shear tested at LNEC, providing interesting information on their residual performance (LNEC, 1997), but no reinforcement was attempted. Strengthening of "frontal walls" with glued Glass Fibre Reinforced Polymer elements (GFRP bars and fabrics) was studied on small-scale new wall prototypes that were shear tested before and after strengthening (Cruz et al., 2001). These tests indicated failure mechanisms and helped identifying weak points and the relative efficacy of several strengthening methods. No research is known, neither about the assessment of traditional light-framed timber partition walls (tabique walls), nor about the variability of these systems or the influence of such variations.

## 5 TRADITIONAL CONNECTIONS

For a better understanding of the mechanical behavior of traditional timber connections is essential to point out the resistant mechanisms of wood under compression. The wood compression strength differs with the stress direction relatively to the fibres orientation. Parallel to fibres, the maximum resistance is achieved and the failure mode can be compared with the buckling instability of cellulose. In the normal direction of fibres orientation, the resistance is minim and the failure mode is associated with the instability of cellulose under radial compression. For compression at an angle to the fibres intermediates resistance values are obtained, which can be quantified following Hankinson formula and adopted by various standards.

Some standards propose different expressions, tanking into account the reduction of resistance caused by the possibility of crushing of the fibres in consequence of the difference between the strength of earlywood and latewood. For instance, SIA 265 (2003) suggests reducing in 20% the resistance of compression parallel to the grain. However, such difference between those two methods became off small account for compression at an angle range of 30° to 60° to the grain, which represents the most realistic values. In addition, some standards take into account the increase in resistance to compression perpendicular to grain resulting from the enlargement of the ratio between the surface loaded and it total.

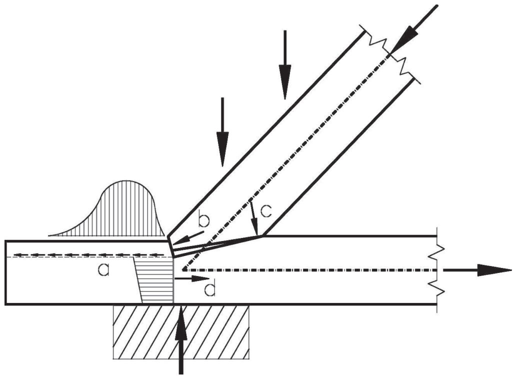



Figure 9. Main resistant mechanism in a traditional timber connection (Piazza et al., 2005).

The design of traditional timber connections comprehends essentially the verification of the compression transmitted between the contact surfaces of the connected elements.

Behind this simple definition, it is important to point out that the contact surface, through which the forces are transmitted, is normally smaller than the cross-section of the element and is not orthogonal to the grain direction of any connected element. In the schematic drawing of Figure 9, reporting a connection between the tie beam and the rafter, which can be assumed as the general example, the main resistant mechanism are presented.

In the design of traditional timber connections, it is essential to understand the force equilibrium in the joint and, therefore, to identify all critical zones verifying for each one its resistance capacity. Analyzing the forces mechanism that occurs inside the joint it is important to draw attention to:

– Existence of not negligible tension perpendicular to the grain often followed by significant shear stresses;
– Concentration of stresses caused by the particular shape of the notches of each connected element;
– Possibility that cracks begin in the step edges;
– Eccentricity in force transmission.

The common design method of traditional timber connections looking out only to the strength characteristics can be explained by several reasons (Larsen & Jensen, 2000):

– The structural design may be very complicated, especially if non-linearity is considered;

– The load–displacement behavior for traditional fasteners is not known with sufficient accuracy;
– Many fasteners exhibit an unpredictable initial (low load level) slip response;
– Lack of realistic semi-rigid models for the connections;
– The deformation capacity is insufficient because of premature brittle failure in tension perpendicular to the grain or shear parallel to the grain.

## 6 CONCLUSIONS

Traditional building construction in Portugal is characterized by a structure made of masonry and timber elements (floors, roofs, interior walls and some exterior walls), which should act together promoting the distribution of load and stiffness. If properly designed and in good conditions, such constructions constitute efficient structures. This type of construction is disseminated all over the country and represents most of our built heritage, justifying the increasing interest on its preservation as memory of culture and identity. Unfortunately, most is degraded and abandoned, demanding urgent actions to re-establish good structural conditions.

Rehabilitation not only preserves the elements as heritage values, as it generates more sustained and respectful interventions, being more close to the recommendations accepted in international charts and documents (*e.g*. ICOMOS, 1999). However, rehabilitation implies a good knowledge on the materials (properties and characteristics) and on the techniques (compatibility and efficiency).

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