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Aging Effect on the Integrity of Traditional Portuguese Timber Roof Structures

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ABSTRACT

Traditional buildings basically include natural and autochthonous construction materials and are built with sustainable construction techniques. The knowledge of these materials's state and construction techniques is required for a proper conservation/renovation work. It is well known that the lack of maintenance is one of the main causes that contribute to the high degree of degradation that the Portuguese traditional buildings unfortunately have. That degradation may even compromise the overall structural integrity of the building thus reducing its lifetime`s expectation. Meanwhile, a partial or even full demolition of a building is still an often occurrence in the Portuguese context. From a sustainable and building heritage perspectives that practise may be inadequate. Taking into account that generally the degradation problems are linked with roof`s leaking anomalies and that the structural components of the roof tend to be the first ones to be affected, this timber structural roof components of Portuguese dwellings were the object of the research work here presented.

KEYWORDS

Aging effect, Used timber, Rehabilitation, Sustainability, Roof structures.

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1 INTRODUCTION

In general, traditional Portuguese dwellings have stone or earth-based masonry materials, timber beams and as the main roof's structural components, timber trusses. The majority of the building materials are both local and natural [Carvalho *et al.* 2008].

These types of buildings have however shown signs of deterioration related to the natural aging of the materials but also as a result of a lack of conservation [Murta *et al.* 2010]. When rehabilitation processes take place it is typically a requirement to identify and to characterise existing materials, to determine their strength capacity such that the aging effect can be taken into account.

Wood is one of the most complex building materials and old or aged wood is even more difficult to analyse because to complete a useful analysis requires the consideration of both the effects of the direct aging of the material and as well, the risk of degradation by external factors. In respect to the risk to degradation by external factors, one must consider that during its lifetime, structural timber elements may be subjected to a variety of biological agents, e.g. fungi, bacteria and insects, which may also modify its material and thus mechanical properties.

Of current interest to the building industry, is a concern for the rehabilitation of building processes and as well consideration for sustainable building practices in which the intent is the reuse of wood. It is in this context that this research work was developed. The intent of the study described in this paper is to examine aging effects on the most relevant traditional timber roof systems used in Portuguese dwellings. For this purpose a real beamed timber roof system was used as a reference point.

This paper is structured as follows: (i) the most common traditional Portuguese roof timber structural system types are identified and briefly described; (ii) one of these systems, namely, the beam solution of a real dwelling is designed according to the current applied regulations; (iii) Considerations relating to the aging effect of timber are delivered; (iv) Some practical design procedures proposed by different authors for dealing with the complexity of aged wood in structural applications are presented. Some additional alternative procedures related to this issue are also proposed; (v) the primary conclusions derived from this study are drawn.

2 TRADITIONAL PORTUGUESE ROOF STRUCTURES

The most common traditional Portuguese roof structures of dwellings are trussed timber systems as shown in Fig. 1-a, or beamed system as depicted in Fig. 1-b. In both cases, the trusses or the beams support the purlins; in turn, the purlins support the boards, which themselves support the roof covering. The traditional type of roof covering may change along the national territory but ceramic tiles are the most widely used in the Portuguese context.

a) Trussed b) Beamed

Figure 1. The most common traditional Portuguese roof timber structural systems.

3 TRADITIONAL PORTUGUESE ROOF STRUCTURE ANALYSIS

The ancient traditional Portuguese roof structures were built based on empirical knowledge in which the experience of the constructors was fundamental. At those times, there were no codes or computer programs that guided the building design processes for these heritage structures. This fact inspired us to verify if an existing traditional roof timber structure was in fact in accordance with the actual applied regulations, in particular that given in ENV 1995-1 [EC5 1998]. For this purpose, the analysis of an existing beamed roof timber system was completed as a "real example" of a solution prior to the implementation of design codes. A timber system consisting of maritime pine (*Pinus pinaster*) of wood E class [EC5 1998] , and part of a dwelling located in the central region of the Portuguese coast was used; its dimensions are given in Fig. 2. The cross sectional area of the existing beams, dimensions of which were collected during an inspection of the structure, is 0.07×0.14 m^2; the beams are placed 0.50 m apart. The permanent and the variable loads acting on the roof (i.e. dead load, wind, snow and seismic) and their respective combinations were defined according to RSA [1985]. An elastic analysis was performed.

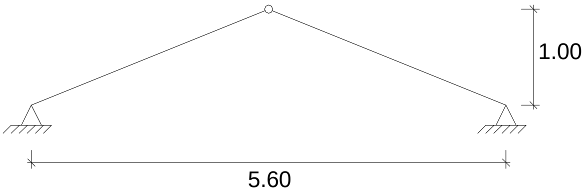
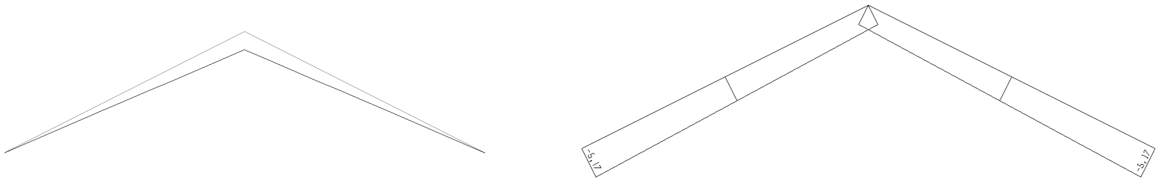
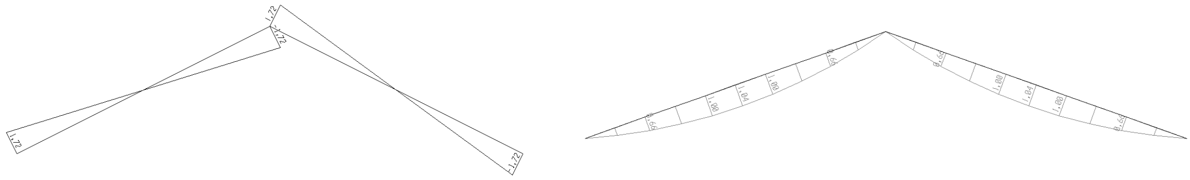


Figure 2. Beamed roof timber structural system model (m).

The most severe combination of loads for this structure was the one related to the dead load. The respective results of both the deformed and forces diagrams are depicted in Fig. 3.



a) Deformed shape (m) b) Axial force (kN)



c) Shear force (kN) d) Bending moment (kNm)

Figure 3. Diagrams.

Using the results derived from the structural analysis and the recommendations given in ENV 1995-1 EC5 [1998], the designed cross section for the beams, if fixing the beam's width to $b = 0.07$ m, corresponds to a section of 0.07×0.05 m^2. Note that this cross section is obtained purely from an academic point of view since in a general sense the element's largest cross sectional area moment of inertia should be mobilized to resist the greatest bending moment. Comparing this result with the existing cross section we concluded that the analysed roof structure is indeed in conformance with the recommendations given in ENV 1995-1 EC5 [1998]. In fact, it is oversized. as well, the aforementioned cross section design resulted from the verification of the ultimate limit state condition when considering bending with compression, or as expressed in ENV 1995-1:

$$\left(\frac{\sigma_{c,0,d}}{f_{c,0,d}}\right)^2 + \frac{\sigma_{m,d}}{f_{m,d}} \leq 1 \tag{1}$$

where, $\sigma_{c,0,d}$ is the compressive stress due to the axial compression force applied parallel to the grain; $f_{c,0,d}$ is the compressive strength due to the axial compression force applied parallel to the grain; $\sigma_{m,d}$ is the flexural stress due to the bending moments and $f_{m,d}$ is the bending stress due to imposed moment on the bean.

4 AGING EFFECT OF TIMBER STRUCTURES

Hoffmeyer stated in Timber Engineering [1995] that wood is a natural, organic cellular solid. It is a composite made of a chemical complex of cellulose, hemicellulose, lignin and extractives. It is highly anisotropic. These are some of the reasons why wood is perhaps considered one of the most complexes building materials with which to design. The analysis of the wood's aging effect, in particular for timber structures, becomes even more complex because it is a time dependent and a process difficult to predict. A timber beam is shown in Fig. 4a that is the remaining element of what was once the timber floor of a traditional Portuguese dwelling. The advanced level of deterioration of this beam is clearly evident in Fig. 4; this level of deterioration was a result of the unprotected conditions in which the beam was to perform and the nonexistence of conservation measures to the beam over time. In this case, the aging effect has been materialized by a progressive process of material degradation complemented by a reduction of cross section as illustrated in Fig. 5.

a) Simple supported beam

b) Detail of the support

Figure 4. Aged timber beam.

Figure 5. Detail of the degradation stage of the left edged of the beam.

We consider that the material degradation corresponds to the material changing due to fungal attack. Its physical properties, such as density ρ, and the stiffness properties, such as the modulus of elasticity *E* and the shear modulus *G*, are all affected. Since this change progresses through time the above material properties become time (t) dependent (i.e. ρ(t), *E*(t) and *G*(t)). This process of progressive material degradation is schematically represented, in a simplified way, in Fig. 6. As illustrated in Fig. 6 the aging effect manifest itself as different layers of material each at specific degradation levels that are formed over time. This scenario suggests that there is an increasing of anisotropy through time and, consequently, an increase in the complexity of modelling aged timber structures.

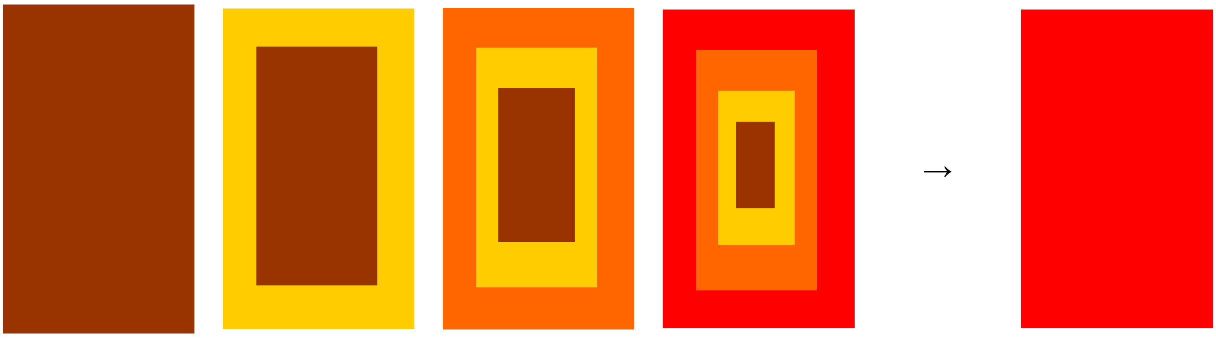


Figure 6. Material properties evolving through time.

Meanwhile, the reduction of the cross section can be due to the attack of insects such as beetles and termites if no treatment measures are taken. Fig. 7 shows, schematically and in a simplified manner, a progressive reduction of a cross section of a timber structural element process through time until no remaining material remains. The area of cross section A and the second moment of inertia I are affected and thus these properties "deteriorate" through this degradation process which develops through time (i.e. A(t) and I(t)). The density is of course also affected in this case.

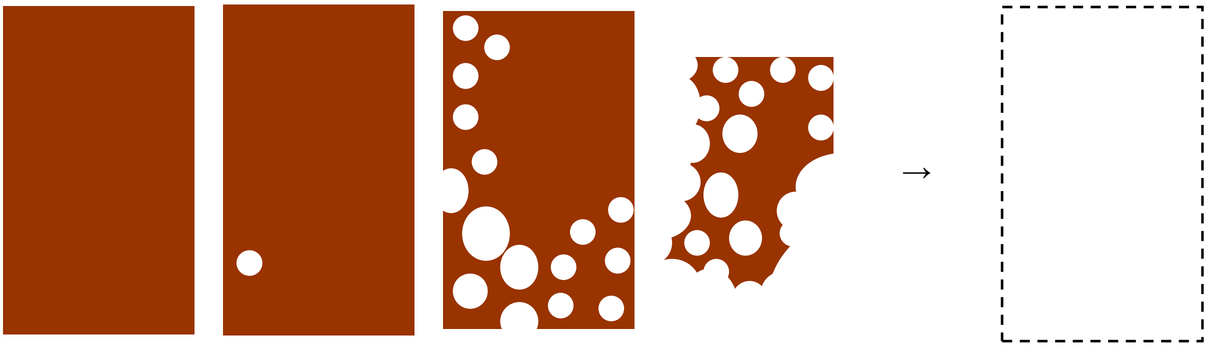


Figure 7. Reduction of cross section through time.

On the other hand, the two degradations processes can take place simultaneously as shown in Fig. 8. In this case, all the above identified properties change through time. Furthermore, it is very likely that there are different levels of degradation among of the different cross sections of a timber structural element. All these aspects drastically increase the complexity of obtaining an accurate numerical model of an aged timber structural element such as the beamed roof timber structural system used as an example in this paper.

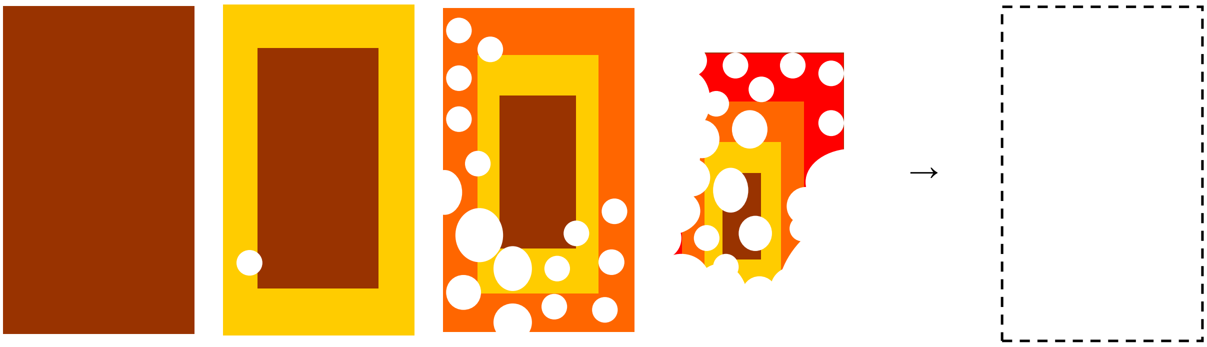


Figure 8. Material changing and reduction of cross section through time.

Taking into account that the variables given in Equation 1 are dependent on the above properties, the design of timber structural elements using aged wood or the structural study of existing old timber elements requires additional care. A future experimental research programme is being prepared, in order to ascertain the effect aging on the structural response of aged timber structures.

5 DISCUSSION AND PRACTICAL SUGGESTIONS

Within the application of ancient timber context, Ross and Wang [2005] suggest that the material properties of old timber require adjustments in order to take into account the aging effect. They stated that the timber elements such as beams removed from old demolished buildings can show deterioration that occurs in over 50% unrecoverable material. However, they also indicated that, in many cases, the amount of waste material is smaller than 10% (i.e. 90% reusable) and that the deterioration was mainly caused by decay (surface and internal), splits, and mechanical damage. Pine wood is of course a species that has been extensively analysed following several years of direct exposure to weathering. In the same context, Marzo [2006] concluded that ancient timber elements may have their original modulus of elasticity decreased by approximately 25% and as a result of several factors, such as: material aging, poor construction labour, weak connections, among others. Meanwhile, Pilt *et al.* [2009] concluded that the ancient timber may have its strength capacity decreased by approximately 15%. In general, these authors propose practical analytical procedures to simplify the previously described complexity related to the aging effect of timber concerning the application of old timber in the building industry. In particular, in a sustainable and economical perspective, this may give guidance for cases like the one shown in Fig. 9.

Figure 9. Coexistent old and new timber structural elements.

For instance, considering the strength classes of *poplar* and *conifer* species which are C14, C16, C18, C22, C24, C27, C30, C35 and C40, the average reduction of bending strength between two subsequent classes is approximately 12%. On the other hand, for three subsequent classes (e.g. C14 and C18) this is about 24%. Note that this value (24 %) is quite similar to the strength reduction proposed by Pilt et *al*. [2009]. Meanwhile, in the example adopted, when performing the design according the legal standards, and not taking into account the aging effect, it was ascertained that the ancient timber structural elements were oversized (see section 3). Within the scope of maintaining or reusing timber and based on the abovementioned facts, an experimental research work is being prepared to access a correspondent smaller strength class for the design purposes in the existence of oversized cross section scenario in order to take into account the aging effect. The reduction strength class decision has to be supported on procedures able to access the extension of the material damaging. In the context of maintaining, these procedures usually have to be performed *"in situ"*. In some cases, the visual inspection might not be accurate enough as it will be unable to predict the internal damaging extension. Furthermore, the density is affected in both material changing and reduction of cross section degradation processes, thus this physical properties may be an adequate parameter for predicting the aging effect in timber structural elements.

6 CONCLUSIONS

A constructed beamed roof timber structural system solution of a traditional Portuguese dwelling was briefly described. This is one of the most common roof structural solutions applied in the context of construction of Portuguese dwelling. The main structural element of this system, a three hinged arch, was designed according to the current applied regulations and it was determined that the existing cross section of the beam was oversized. The aging effect of the timber was not taken into account in this analysis.

Some considerations related to the description of aging effect in timber were offered. It was highlighted that biological phenomena may attack and deteriorate the structural timber elements progressively through time. If no treatment measures are taken to conserve the timber elements, these may degrade and could eventually collapse. Since the physical and mechanical properties, the stiffness and the strength properties are affected during aging and since they are also an analytical function on time. These aspects increase significantly the complexity of this problem.

It was presented some practical measures proposed by different authors to deal with this complexity. In this paper, other practical measures were suggested which intend to contribute to bringing some clarity to this issue.

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