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Assessment of timber element mechanical properties using experimental modal analysis

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HIGHLIGHTS

- A set of eight Douglas-fir beams were tested.
- A Python-MatLab script was created to perform the modal updating.
- A sensitivity analysis was conducted to reduce to number of unknown parameters.
- A validation with existing classical techniques has been achieved.
- Obtained results are insensible to local defects.

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ABSTRACT

Nowadays, timber frameworks become one of the most widespread types of material in building constructions. Their configurations and joints are usually complex and require a high level of craftsmanship to assemble. To properly assess the behaviour of timber elements, many assessment techniques are available but they present some limitations. This paper presents a non-destructive approach to finite element updating using results from experimental modal data. Several timber beams in a free supported condition were analysed in order to extract the frequency response functions and their bending natural characteristics (frequency, damping and mode shape). A finite element model was derived, taking into account the possible effect of local defects. With the intent to estimate the corresponding mechanical properties, a procedure of modal updating was carried out by implementing various modal criteria. The objective function was selected from the conventional comparison tools (absolute or relative frequency difference, and/or modal assurance criterion). This assessment tool was tested to determine the mechanical properties of timber beams (elastic moduli and damping properties). To verify the modulus, a series of static 4-point bending tests and STS04 classifications were conducted. In addition, sensitivity analysis reduced the number of parameters to be updated (Young's modulus along the beam length and the corresponding shear moduli), showing that the present method is an efficient alternative to conventional wood tests.

1. Introduction

Protection and shelter against wind, rain and cold are very basic needs for mankind. For a long time, wood was the most commonly used material in the world. All over the world, examples of religious buildings or housing constructions attest to the specific and important skills of builders through the centuries. In Asia and Europe, existing timber structures that date from the 7th and 8th century are still standing today. Of course, they suffer from various pathologies and most of the time they have been a field of experimentation for all building restorers over the centuries. One major issue when using timber in construction is its susceptibility to humidity that might arise in buildings. The main issue is not so much the reduction of the properties but is more the risk of biodegradability by fungus or insects. These kind of pathologies are well known by building restorers who deal with old timber structures.

Despite the fact that, from the mechanical point of view, there is no ageing issues of timber elements when they are properly used [2], many old timber structures require important interventions because of changes in uses (which modifies the regulation rules for example), of material decay (misuse of timber) or possibly of a faulty design or construction. An important difficulty in

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approaching conservation projects of timber structures is the structural assessment, in addition to all others relevant dimensions of the project (architecture, historical, archaeological, ...). Timber is a natural material which means that there is little control over its growth or over natural defects (knots, for example) which influence its properties. Furthermore, while timber elements may present a high variation of properties between species, there can also be variations within one species [3]. Knowing the timber species and grades used in the structure is of huge importance for restorers, an overly conservative assessment of the mechanical properties may lead to wrong decisions and unnecessary interventions. Whatever they are, replacements or repairs, pointless interventions are detrimental to the original timber structure and entail superfluous costs.

Many techniques have been developed for the structural assessment of timber beams [1] which is only one component of the whole assessment of an old timber structure [4]. Unfortunately, most of the non-destructive testing (NDT) methods available are not useful for a quantitative description of the strength properties. Ideally, the quality assessment of timber elements aims for assigning structural grades (without causing any degradation of the tested element) thanks to grading rules based on a given technique and limited to given species. Techniques used can be classified into three main categories: destructive, semi-destructive and non-destructive according to their "impact" on the tested sample. To better understand the interest of the proposed method, Table 1 lists the main drawbacks and advantages of the most spread techniques used for the assessment of *in situ* timber members. Those ones, associated to a fiddly assessment of the location and spreading of the deterioration (biotic deterioration) are good prediction tools for the structural analysis of the structure.

Timber is one of the oldest known building materials but it does not mean that we have a deep scientific knowledge of its behaviour. For structural uses, many aspects of the modelling of timber as an engineered material still remain challenging. Timber is a porous fibre-composite material whose properties are affected by moisture content (increasing the water content of wood lowers its strength) [5]. The cellulose fibres are "glued" along a complex 3D line in matrix what results in a macroscopical anisotropic behaviour. Timber presents a strong anisotropy because up to 90 or 95% of all the cells are aligned parallel to the tree trunk. The consequence is the definition of different mechanical properties along the longitudinal, radial and tangential directions (Fig. 1), hereafter noted directions 1, 2 and 3, respectively. So, the elastic constitutive law, modified to take into account the anisotropy of clear wood can be written as follows:

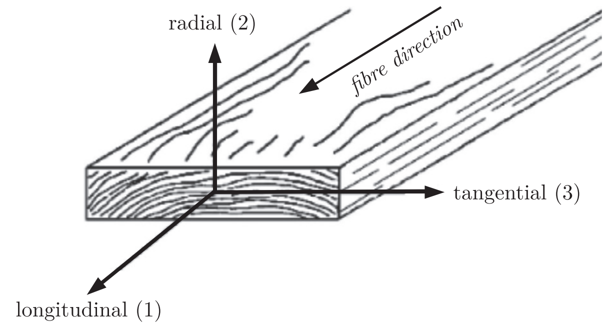

Fig. 1. Orthotropic directions for a clear wood sample.

$$\begin{Bmatrix} \epsilon_{11} \\ \epsilon_{22} \\ \epsilon_{33} \\ \gamma_{12} \\ \gamma_{13} \\ \gamma_{23} \end{Bmatrix} = \begin{pmatrix} \frac{1}{E_1} & \frac{-\nu_{21}}{E_2} & \frac{-\nu_{31}}{E_3} & 0 & 0 & 0 \\ \frac{-\nu_{12}}{E_1} & \frac{1}{E_2} & \frac{-\nu_{32}}{E_3} & 0 & 0 & 0 \\ \frac{-\nu_{13}}{E_1} & \frac{-\nu_{23}}{E_2} & \frac{1}{E_3} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_{12}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{13}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{23}} \end{pmatrix} \begin{Bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \sigma_{12} \\ \sigma_{13} \\ \sigma_{23} \end{Bmatrix} \qquad (1)$$

where the stress σ_{ij} acts on the plane normal to the i-direction and along the j-direction (so, $i = j$ for normal stresses and $i \neq j$ for shear stresses). ϵ_{ii} and γ_{ij} are the normal strain in i-direction and the shear strain along the plane ij, respectively. The matrix in brackets is the compliance matrix of wood. As timber exhibits symmetry in its elastic response, only nine elements are independent: three Young's modulii E_i, three Poisson's ratios ν_{ij} and three shear modulii G_{ij}. The zero elements in the matrix attest the lack of coupling between the normal and shear components in this model. Because the compliance matrix must be symmetric, Poisson's ratios and Young's moduli are related by

$$\frac{\nu_{ij}}{E_i} = \frac{\nu_{ji}}{E_j}, \qquad i \neq j. \qquad (2)$$

Carry out full-scale ambient or forced vibration experimentations on a structure may be used to get its dynamic characteristics: natural frequencies, damping ratios and mode shapes. Among all studies made in this field of research, to perform a finite element simulation of an old church, Aras et al. [6] detected the modulus of elasticity of the masonry by using the operational deflection shape method. Sánchez-Aparicio et al. [7] developed a methodology going from the data acquisition to the finite element modelling

Table 1
Comparison between the different techniques for wood characteristics assessment (information extracted from [1]).

Techniques	Advantages	Drawbacks	Estimatedparameters
Sounding method	Rapid screening of the decay	Highly subjective Qualitative information	/
Ultrasonic technique	Quick analysis Cheap method Reliable and consistent results Extent of the decay	Quite complex Model preparation 3 directions measurements	E, ρ moisture content
Vibration method	Only one member face required Quick and simple	Influence of wood attenuation	Mechanical properties (modulus of elasticity – MOE)
Acousto ultrasonic method	Determination in the 3 axis Recognize heterogeneities	Same to the ultra-sonic technique	Same to the ultra-sonic technique Defaults detection
Radiography	New equipment highly portable	Limitations in the obtained information Security	Dimensions, cracks deformations and even strains
Ground penetration radar	Portable GPR available Identification of common defects Good repeatability Tolerance to imperfect surfaces	Portable GPR configured for concrete applications Badly suited to detect thin defects Data interpretation and post processing complicated	Geometry characterization Detect of the defaults