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Evaluation of cross-sectional variation of timber bending modulus of elasticity by stress waves

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HIGHLIGHTS

- An indirect sonic stress wave method to predict the modulus of elasticity of a timber member was studied.
- The cross-sectional spatial variability of timber members was taken into consideration.
- This procedure provided a medium-high correlation and an average-low prediction error.

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ABSTRACT

Serviceability limit states (related to deformation) rather than ultimate limit states (related to collapse) are often the reason for the need to assess existing timber structures. Prediction of timber members' stiffness is often accomplished using stress wave testing methods. However, these methods only provide information about the quality of the outer layers of the timber members. For a more reliable prediction assessment, one should acknowledge the spatial variability of timber's mechanical properties, especially considering the gross cross-section of old timber members. Here, it was studied the capacity of an indirect sonic stress wave method to predict the modulus of elasticity of a timber member, taking into consideration its cross-sectional spatial variability. The results show that this procedure provides a medium-high correlation ($r^2 = 0.91–0.94$) and an average-low prediction error (~7%). The prediction of density showed reliable results when done using wood cores where as a poorest prediction was obtained by the drilling resistance method used in this work.

1. Introduction

In recent years, a general awareness of the necessity to rehabilitate our building heritage has grown, resulting in the publication of guides for the structural rehabilitation of existing buildings, especially covering those having heritage value [1,2]. Economic and cultural factors, allied to issues such as sustainability, increase the pressure on rehabilitation works to restore the built heritage and decrease the level of waste. The replacement of deteriorated elements may not be an acceptable option for structures of historic significance; redesign may be necessary to sustain functionality [3]. Timber is a building material often found as structural elements in historical constructions, given its availability at the time of erection and its good mechanical properties (e.g. the high strength/weight ratio).

A reliable structural analysis of existing timber structures constitutes a crucial support decision tool regarding efficient repair or strengthening solutions, thus ensuring the safety and serviceability of the structure. Both timber elements and joints must be characterised, and both the present state of conservation and the evolution of performance must be considered [4].

Currently, the timber structure diagnosis process is carried out by visual grading together with non-destructive testing (NDT) or semi-destructive testing (SDT) methods [4]. Visual inspection allows to evaluate the condition of the structure (i.e. structural system, structural defects, deformation of timber members, signs of deterioration); the loading conditions (i.e. deviation from intended use that can result in overloading); the additions to the original structure and their effect on the original structural system; the quality of timber (knots, cracks, slope of grain, etc) and allocation of visual strength grade and consequent characteristic values or a strength class; and the location of critical areas for further inspection [5].

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Frequently, the results obtained from visual inspection are complemented with information from NDT and/or SDT methods, such as stress wave or ultrasound, thermography, screw withdrawal, drilling resistance, digital radioscopy, etc. [4]. However, the necessary degree of specialisation and knowledge about the application and limitations of each testing method and the lack of standardisation about their usage are the major drawbacks for their more general use.

Regarding the assessment of mechanical properties, stress waves are generally applied either using sonic or ultrasonic frequencies. These non-destructive testing (NDT) methods are used to predict the dynamic modulus of elasticity, its result being affected by several factors such as moisture content, wood species and growth ring orientation [6]. Usually, stress wave testing is conducted in one or more surfaces of the member over an area showing no defects. The possibility of extrapolating the clear wood modulus of elasticity to the entire element is supported by the fact that the modulus of elasticity is mainly affected by the basic quality of a structural member and is less affected by local defects [7]. Stress wave testing onsite is based on an indirect method where the transducers are placed in the same surface. For this reason, only the outer layers of the timber members are tested. Wood is an anisotropic material showing high variability in physical and mechanical properties in a same section and along its length. For gross cross sections, this variability is higher in cross-section than along the length [3].

In the assessment of timber members, this variability is expressed by the large coefficients of variation to be used in conjunction with the mean values obtained from NDT/SDT methods [8]. For pine wood, a variation between juvenile and mature wood of 50% could be expected [9]. Also, the variability expected for a timber member is defined by JCSS probabilistic model code as 25%, 13% and 10% for bending strength, bending modulus of elasticity and density, respectively [10].

The objective of this study was to interrogate the feasibility of assessing the variation of bending modulus of elasticity across the cross section of structural timber members using a stress-wave semi-destructive method. For this purpose, Fakopp's Tree sonic equipment was used. This equipment was designed for foresters and has become increasingly popular in forest and processing environments [11]. Its popularity arises from the tool being relatively inexpensive, simple to use, and because it permits non-destructive testing of wood samples (or semi-destructive, depending on the fact of the spike mark effect upon the cultural integrity of the element). For the determination of the dynamic modulus of elasticity it also needed the density of the timber element. For this purpose two methods were compared: wood cores; and, drilling resistance. The first one provides a direct measurement of density while the other provides an indirect evaluation. For the resistance drill a new method was envisaged from the work performed by [12].

2. Material and methods

2.1. Material

Test pieces were cut from clear wood zones of maritime pine (*Pinus pinaster* Ait.) timber beams with dimensions 2000 × 160 × 90 mm^3 (length × height × width). A sample of 30 clear wood pieces with dimensions 550 × 160 × 90 mm^3 (length × height × width) was obtained. In the selection of these pieces it was accepted knots with a diameter equal of inferior to 10 mm. From this point forward, these test pieces will be designated as TP. Considering the effect of growth rings on ultrasound readings, the pieces were divided into two groups of 15 samples according to growth ring curvature in the cross section. In sample A the growth rings are parallel to the larger longitudinal surface of the test pieces, whereas in sample B, the growth rings make an angle (of around 45°) with the same surface (Fig. 1).

2.2. Methods

The experimental procedure was divided into two steps. In the first step, the TP were tested using non- or semi-destructive testing methods (e.g. stress waves, ultrasound, drilling resistance and core-drilling). In the second step, the TP were cut to obtain five small clear wood specimens (SCWS: Fig. 2). So, there were five specimens from each test piece. SCWS were tested in static bending to obtain the static modulus of elasticity. These same specimens were also used for the determination of moisture content and density.

All the wood specimens was conditioned and tested inside a room with controlled temperature (20 ± 2 °C) and relative humidity (65 ± 5%).

2.2.1. Sonic stress wave method

In each test piece, four stress wave measurements were carried out at different depths. The stress wave time-of-flight was determined by placing the transducers in the same surface (indirect method) (Fig. 3).

A Fakopp Microsecond Timer equipment with two transducers and an integrated 25 mm-long spike was used. The measurements were made in both edges of the specimen. For each edge, the first reading was made in the external layer by a spike penetration of approximately 10 mm. The transducers were placed 43 cm apart and were driven into the wood at an angle of ~45° angle (Fig. 4). After the first readings, a larger hole was produced with a depth equal to the penetration of the spike using a drill bit diameter of 7.5 mm. In this case, the transducers were placed 40 cm apart. The diameter of the internal passage hole allowed the spike to be driven into the next 10 mm of wood, avoiding in the first 10 mm any contact between the spike and wood (Fig. 4). To minimise errors at each depth, eight readings were taken, and the average taken as the time-of-flight (TOF) for that particular section.

The average TOF was then used along with the distance to predict the stress wave velocity parallel to the grain (v).

The dynamic modulus of elasticity (E_{dyn}) was obtained from Eq. (1), using for the density (ρ) predictor the average value of the density obtained from two wood cores taken in the vicinity of the transducers.

$$E_{dyn} = v^2 \cdot \rho \ (N/m^2) \tag{1}$$

2.2.2. Ultrasonic indirect method

A PUNDITplus equipment using 54 kH probes was used. A mineral gel was used to ensure an efficient coupling between the probes and timber's surface. A one-shot impulse transmission was applied. The probes were placed 40 cm apart (minimum distance between probes perimeter) at the upper edge of the test specimens. Only one surface was tested, since the procedure is usually performed in situ. Ten measurements of the wave velocity were carried out in each test piece. The average velocity value was taken as the reference value of each test piece. A spring was used to maintain the same pressure all over the tests and to ensure the proper interface probe-wood surface (Fig. 5).

The dynamic modulus of elasticity was determined (Eq. (1)), using (as for the sonic method) the average density value obtained from the wood cores.