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A comparative study of using static and ultrasonic material testing methods to determine the anisotropic material properties of wood

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HIGHLIGHTS

- Comparative analysis of static and ultrasonic testing for wood.
- Determination of all twelve orthotropic material properties of two hardwood species.
- Recommendations on the execution of the static and ultrasonic tests for wood.

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ABSTRACT

This paper presents a comparative study using static and ultrasonic testing for the determination of the full set of orthotropic material properties of wood. In the literature, material properties are typically only available in the longitudinal direction, and most international standards do not provide details on the testing of the other two secondary directions (radial and tangential). This work provides a comprehensive study and discussions on the determination of all twelve orthotropic material properties of two hardwood species using static testing and an alternative testing approach based on ultrasonic waves. Recommendations are given on the execution of the tests and the interpretation and calibration of the results.

1. Introduction

Wood is an anisotropic material, which, in terms of elastic models, is characterised as an orthotropic material. As such, it has unique and independent mechanical properties in the directions of three mutually perpendicular axes: longitudinal, radial, and tangential [1]. As orthotropic material, wood is defined by twelve constants (nine independent), which describe its elastic behaviour: three moduli of elasticity (MOE), three moduli of rigidity (G), and six Poisson's ratios ν. Typically, these material properties are determined through static testing, which involves the destructive testing of small test specimen, and includes mechanical testing methods such as four point bending, compression and tension tests. Since for engineering purposes, the superior characteristics of wood parallel to the grain are mainly utilised, it is mostly the MOE in longitudinal direction that is normally of interest. Consequently, MOE values in the radial and tangential directions are very scarce in the literature. Furthermore, it is very difficult to determine the radial and tangential material characteristics, and international standards do not provide full details on the mechanical testing of the material properties in the two secondary directions of wood. Only standard EN 408:2010 [1] gives some criteria for the determination of a selection of mechanical properties perpendicular to the grain direction.

Most values of the longitudinal MOE reported in the literature commonly describe the MOE derived from bending tests (MOE_B), which are normally different from MOE values derived from tension or compression tests. Schneider et al. [2] investigated variations between MOEs derived from bending, tension and compression test on sugar maple at 12% moisture content. The researchers found that the determined values ranged from 15.1 GPa for the MOE in compression (MOE_C) up to 16.5 GPa for the MOE in tension (MOE_T). Wangaard [3] compared the MOEs

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derived from bending and compression tests of several wood species and found that the values determined from compression tests were somewhat higher than the ones derived from bending tests.

Since static material testing is very time consuming and provides only an approximate evaluation of a large batch of material on the basis of testing of a small sample population [3], it is unsuitable for determining the material properties of in-situ structures, in particular due to its destructive nature. Hence, an attractive alternative to destructive static testing is non-destructive testing (NDT) or non-destructive evaluation, which is defined as the technique of identifying the physical and mechanical properties of an element of a given material without altering its final application capacity [4]. NDT methods have long been used on timber to assess structures without causing damage, and involve a wide group of analysis techniques. The earliest non-destructive evaluation of wood is visual inspection, which has mainly been used for the selection of timber for construction purposes. Even nowadays this method is still widely used for grading wood products such as lumber, piles and poles. NDT methods also allow the evaluation of in-situ structures, enabling their maintenance or rehabilitation through the mapping of the deteriorated areas, permitting the assessment of their structural integrity without the need to remove part of the structure [5].

In the early 20th century, scientific NDT methods became available with the development of the theory of elasticity and more advanced measuring equipment to determine the material properties of wood. Ross [4] described the use of several techniques, including X-rays, vibration analysis and sound wave transmission, used to characterise wood non-destructively. Hearmon [6] and Kollmann and Krech [7] were the first researchers in Europe who conducted research on the determination of the MOE based on dynamic methods. Hearmon [8] was the first to promote NDT techniques using ultrasonic waves for the elastic characterisation of wood. And McDonald et al. [9] stated high correlations between the MOE obtained from acoustic wave and static deflection techniques.

For ultrasonic testing, an ultrasonic wave is induced into a material through an ultrasound transmitter (ultrasonic transducer) and the wave transmission time over a known distance is measured [10]. The measured "time of flight" and the known distance are used to estimate the wave velocity, which is the basis for determining various material properties. For the ultrasonic testing of wood, the applied ultrasound frequencies are typically in the low range between 20 kHz and 500 kHz, due to the high attenuation which occurs in wood. Depending on the direction of grain (longitudinal, radial or tangential), the waves travel through wood with different velocities. The wave velocities in the longitudinal direction are the highest and range from 3050 to 6100 m/s as reported by Gerhards [11], who determined these values on small clear wood specimens with a moisture content of 9–15%. The velocities in radial and tangential direction are usually around a third of the longitudinal wave velocity, with the radial direction featuring slightly higher velocities than the tangential direction [12]. This is due to the fact that the anatomical elements, such as fibres and tracheid, are aligned in longitudinal direction and the wood rays in radial direction, while in tangential direction, along the annual growth rings, no structural elements exist. In addition, the annual rings behave as a barrier for elastic wave propagation resulting in reduced wave velocity. Several factors influence the wave velocity in wood, the most important of which is the microscopic and macroscopic structure of wood, where the microfibril angle and the length of the anatomical elements play a vital role. Bergander and Salmen [13] demonstrated that a small cell wall layer results in a high longitudinal MOE, with corresponding higher acoustic wave velocities. The influence of wood density on the wave velocity has been the subject of several studies, with different researchers arriving at a variety of conclusions. Bucur and Chivers [14] found that an increasing density leads to slower wave propagation velocities, while Oliveira et al. [15] observed the opposite behaviour. Other researchers stated that the density does not have any influence on the wave velocity [16,17] or that it has a positive effect but is suppressed by other factors such as the micro and macro structure of the material [18].

MOE values obtained from ultrasonic testing are generally higher than those determined through static deflection [5]. Smulski [19] reported on dynamically determined MOE values for four hardwood species (maple, birch, ash and oak), which were between 22% and 32% higher than statically obtained MOE values from bending tests. Similar values were also presented by Burmester [20], with dynamic MOE values being 19–34% higher than the static MOE values derived from bending tests on beech and two tropical hardwood species. According to Halabe et al. [21], this is because wood is a viscous elastic and highly impact absorbent material. As such, for wood, the restored elastic force is proportional to the displacement and the dissipative force is proportional to the velocity. Hence, when a force is applied for a short time, the material shows a solid elastic behaviour, while for a longer application of a force, the behaviour is more similar to that of a viscous liquid. This behaviour is therefore more evident in static bending tests (long duration) than in ultrasonic testing. And thus, the MOEs determined from ultrasound measurements are usually larger than those obtained from static testing [5].

This paper presents a comparative study on the determination of the full orthotropic material properties of wood using traditional static testing and dynamic testing based on ultrasonic stress waves. For two hardwood species, Spotted Gum (*Eucalyptus Maculate*) and Tallowwood (*Eucalyptus Microcorys*), all 12 elastic material properties (moduli of elasticity, moduli of rigidity and Poisson's ratios – in longitudinal, radial and tangential directions) are determined from static and ultrasonic testing. The obtained values are compared against each other as well as against literature values (where available). For the static testing, the strength properties (modulus of rupture, the compression strength and tensile strength) are also determined. For the investigation, wood from two pole specimens, of Spotted Gum and Tallowwood, are tested. For the static testing approach, four-point bending, compression, tension and Poisson's ratio tests are undertaken on full pole sections as well as small clear specimens produced from the same poles. The ultrasonic testing is conducted on full pole sections, cross-sectional pole sections and wood block specimen also manufactured from the same pole specimens. Since international standards only fully cover mechanical testing of wood in longitudinal direction, testing procedures for the radial and tangential directions are proposed and evaluated. MOE values are determined from different static testing methods (bending, compression and tension tests) and their results are compared against each other.

The presented study is believed to be the first to provide the full material properties of the two investigated wood species, Spotted Gum and Tallowwood. It also provides valuable information on the mechanical testing of wood in radial and tangential direction. Most importantly, it presents a comparative analysis of using static and ultrasonic testing approaches for the determination of the full material properties of wood.

As such, the focus of the presented research is to compare the different testing methods and results. The aim is not to test as many poles as possible, which has been done previously in other studies in order to gather information on the variation of the material properties within a species. The focus of this research is on the methods themselves, which require material of consistent properties to exclude additional uncertainties as introduced by varying material characteristics.