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# Experimental characterization of longitudinal mechanical properties of clear timber: Random spatial variability and size effects

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## HIGHLIGHTS

- Length effect on elasticity and tensile strength of clear spruce was investigated.
- Mesostructure and local elastic modulus relation was studied.
- High elastic modulus variability was measured.
- An upper bound for the strength of small specimens was observed.

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## ABSTRACT

In this study, an experimental campaign was conducted to characterize the length effect on the elasticity and tensile strength of clear spruce wood parallel to the grain direction. Four groups of specimens of different lengths, cut from the same log, were tested under the same conditions under longitudinal tensile loading. The cross-sectional area of the specimens was selected as being constant and sufficiently small to exclude the effect of variations of the properties in the transverse direction. Local deformations along the lengths of the specimens were recorded during the tests in order to characterize the spatial variability of the elastic modulus. A connection between the mesostructure of the clear wood and its local elastic modulus was observed. Statistics concerning the elastic modulus, strength and strain to failure and the effect of length change on these properties were extracted. The strength statistics were also used to examine the accuracy of the classical Weibull size effect law. The correlations between the strength, the elasticity and the density were obtained. The results show a variability of approximately 20% in the local elastic modulus. Also, the variability of the effective elastic modulus decreases with increasing length. The mean value of the strength has an upper bound when the length approaches zero, in contrast to the Weibull law, while its variability remains virtually unchanged for different lengths.



## 1. Introduction

As a natural unidirectional fiber composite, wood/timber has highly anisotropic properties [1]. Different factors such as age, location of timber within the tree, structural imperfections, load history such as wind and snow etc. can affect the material properties of timber taken from the same species, and grown in the same geographical location and local growth conditions. Consequently, there is a considerable variability in mechanical properties. This variability, also observed in other materials such as composites, is both random and spatial and is usually referred to as "random spatial variability" [2,3].

The effect of the high scatter of timber elastic properties [4] on the response of timber structures has received less attention in the literature than the effect of the scatter of strength. In the few works that take the statistical variability of the elastic modulus into account, when assessing the structural response, the local point-by-point variability, i.e. the spatial variability, is commonly neglected [5,6]. This local variability of the elastic modulus can affect the local stress state of the material, which can be critical in estimating the failure probability under external loading. Recently Arwade et al. [7] have experimentally characterized the longitudinal spatial variability in the elasticity of parallel strand lumber using bending tests. They incorporated the experimental results in a stochastic model with orthotropic elasticity.

The mean strength of timber decreases as its volume increases due to the size effect on the strength. A small number of works

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have used pure tensile tests, on specimens of different sizes, to investigate the size effect on the strength of clear timber. In [8], a length effect parameter was introduced by Zhu et al. to quantify the size effect, due to the length change, on the longitudinal tensile strength of Japanese larch wood. Dill-Langer et al. [9] conducted longitudinal tensile experiments on two groups of specimens composed of spruce wood, and observed that the volume of the material significantly affects the strength. The term clear timber in this paper is equivalent to clear wood suitable for building and construction.

The classical Weibull size effect law (CWSEL) [10] is commonly used in the literature for modeling this effect [5,6,9]. Some researchers have considered this effect as a volume effect. For example, this assumption was applied in [11–14] for the failure analysis of adhesively-bonded, welded and dovetail timber joints and in [5,6,15] for the study of the elastoplastic behavior of strand-based wood composites and laminated veneer. Others, however, have split this effect into length and cross-sectional effects, see e.g. [16,17] on the bending strength of clear timber and [18] for the case of structural lumber. Nevertheless, in a recent study [19], it was highlighted that "Although no conclusive evidence has yet arisen concerning the accuracy of probabilistic strength theories to describe the size in the strength of timber, the existence of significant size effects is largely accepted within the scientific community."

The spatial variability is most likely to influence the response of structural elements made of clear timber, such as bonded and mechanical joints, which has not been previously studied. This work is an attempt to investigate the random spatial variability of the timber elastic modulus. Also, it is partly aimed at experimentally characterizing the size effect on the strength of clear timber using specimens of different lengths, which can be used for developing more accurate models for the size effect on timber strength. This work is focused on clear timber properties at mesoscale and does not investigate the properties of timber boards with defects.

Four groups of specimens of different lengths were prepared and their quasi-static behavior was experimentally investigated under tensile loading. In addition to the global displacement monitoring, the local deformations along the length of each specimen were measured. The effect of the mesostructure of the clear timber on the local elastic modulus was examined. The spatial variability of the elastic modulus was experimentally characterized. Also, Statistics concerning the elastic modulus, strength and strain to failure as well as correlations between elastic modulus, strength and density were derived. Moreover, the size effect on these properties due to the length change was studied.

## 2. Experimental investigation

### 2.1. Material

Norway spruce wood was used for the specimens' preparation in this study. Although the boards contained a certain number of knots, the specimens were cut sufficiently far from these defects. All specimens were conditioned to 12% moisture content according to the ASTM standard D143-14 in a conditioning chamber and were tested at the laboratory temperature of 22 ± 3 °C. The average density of the wooden specimens after conditioning was 443.3 kg/m$^3$.

### 2.2. Specimen description

Specimens of different lengths were fabricated for the purpose of this study. In order to exclude variations in the properties in the cross-sectional plane, the nominal cross section of the specimens had to be as small as possible and yet it had to be possible to fabricate them well using a CNC machine. Due to these requirements, a new specimen geometry for longitudinal tensile tests on timber was designed. This geometry is shown in Fig. 1. The gradual change in the dimensions of the cross-sectional area, from the gripping part to the middle part, via two connected curves, provides an appropriate smooth stress distribution. Moreover, this specimen is easy to fabricate since it has an extruded geometry.

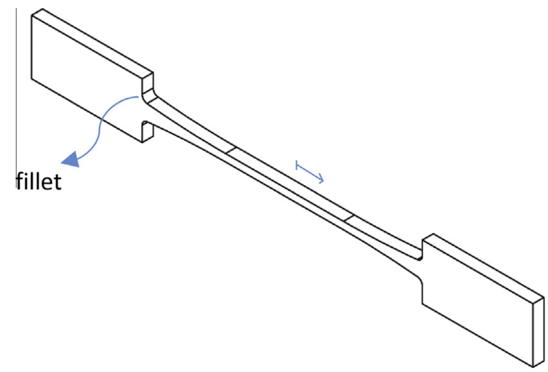


**Fig. 1.** Specimen geometry designed for tensile tests. The straight arrow shows the longitudinal timber direction.

The specimen's geometrical configuration is shown in Fig. 2a. The cross section of the middle part is a square of 2 × 2 mm$^2$. In Fig. 2a, L denotes the length of the middle zone of the specimen with the values of 2, 8, 32 and 128 mm. Sample specimens are shown in Fig. 2b. Specimen edges were carefully treated with very soft sandpaper, P240, to remove the cutting residual.

The following system is used to refer to the specimens in this study: LT-abc-4-de where 'LT' refers to longitudinal tensile, 'abc' is the specimen length in mm, 4 is the cross-sectional area in mm$^2$ and 'de' is the specimen number within a group of specimens with the same geometry. In the next sections, it is seen that the strengths of the four specimen sets with different lengths, although cut from different boards, show approximately the same level of scatter. This demonstrates that a sufficient number of specimens in each group have been considered to capture the randomness of the properties of the material used.

### 2.3. Experimental set-up and instrumentation

All experiments were carried out on a 25-kN MTS Landmark servo-hydraulic testing machine with a built-in load cell calibrated to 20% of the full capacity. Quasi-static tensile tests were performed under displacement-control mode. Different stroke rates for different lengths were selected on the basis of the pre-testing of additional specimens so that the final failure occurred within 180 ± 60 s during the whole testing program. A constant stroke rate among different groups was not used because the specimen sizes were different. Due to the scatter in the strength and stiffness, the failure time varied for specimens with the same geometry.

A video extensometry system composed of a 10-bit Sony XCLU1000 CCD connected to a Fujinon HF35SA-1 lens, with a focal length of 35-mm and an aperture, f 1.4–22, able to provide an accuracy of ±0.005 mm, was used during the tests to measure the axial deformation. Prior to the tests, small black target dots of 1.3-mm in diameter were applied on the specimens' surfaces as shown in Fig. 3 for a specimen of 32 mm-length. The distance between each two consecutive dots was 4 mm for all groups of specimens, except for specimens with a nominal length of 2 mm, where the distance between the two dots was 2 mm. The axial coordinates of the dots were recorded at a frequency of 5 Hz by the camera throughout loading. Using these data, the strain between each two consecutive dots was calculated. The axial stresses were also calculated using the load level and the initial cross-sectional area.

## 3. Timber mesostructure and local mechanical properties

The mesostructure of clear spruce wood is mainly characterized by the earlywood-latewood patterns which affect the local mechanical properties. This is the origin of random spatial variability in the properties. Some of these mesostructural features observed in the specimens are shown in Fig. 4. The darker parts of the growth rings are latewood that has higher mechanical properties, referred to as strips of latewood. Although all the specimens were cut in the nominal longitudinal direction of the board, the fiber direction along the specimen length is often not parallel to the specimen axial direction. Fig. 4a illustrates the fiber misalignment with respect to the nominal longitudinal direction of the board. This misalignment can reduce the local longitudinal elastic modulus, however, it is not related to the specimen misalignment, since all specimens were cut parallel to the nominal longitudinal axis of the timber boards. Another consequence is that at some