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Determination of the elastic and stiffness characteristics of cross-laminated timber plates from flexural wave velocity measurements

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ABSTRACT

Cross-laminated timber (CLT) is an engineered wood with good structural properties and it is also economically competitive with the traditional building construction materials. However, due to its low volume density combined with its high stiffness, it does not provide sufficient sound insulation, thus it is necessary to develop specific acoustic treatments in order to increase the noise reduction performance. The material's mechanical properties are required as input data to perform the vibro-acoustic analyses necessary during the design process. In this paper the elastic constants of a CLT plate are derived by fitting the real component of the experimental flexural wave velocity with Mindlin's dispersion relation for thick plates, neglecting the influence of the plate's size and boundary conditions. Furthermore, its apparent elastic and stiffness properties are derived from the same set of experimental data, for the plate considered to be thin. Under this latter assumption the orthotropic behaviour of an equivalent thin CLT plate is described by using an elliptic model and verified with experimental results.

1. Introduction

Cross-laminated timber, often abbreviated to the acronym CLT, is an engineered solid wood material consisting of an odd number of layers of wooden beams glued together, alternating perpendicularly the orientation of the fibres of each ply. CLT building panels are generally fabricated with three, five, or seven layers, according to the static requirements, with a total thickness up to 500 mm. According to the standard EN 16351 [1] the thickness of each layer should be within the range 4 – 65 mm. The success of CLT plates has continuously been increasing in the building construction market over the last twenty years. Its high strength, good structural stability, fulfilment of safety requirements together with the cost competitiveness and the possibility to rapidly assemble prefabricated panels, make CLT a valuable alternative to traditional building construction materials such as concrete, masonry and steel. However, due to their high stiffness combined with their low density, CLT structures do not provide satisfactory noise reduction. Therefore, in order to improve sound insulation performance, it is necessary to design and optimize specific acoustic treatments, such as additional layers applied to the walls [2], like gypsum board linings on a cavity, or a concrete floating screed over the CLT floor structures [3]. Most of the

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prediction methods to compute structure-borne and air-borne sound transmission require the geometric characteristics of building elements and the materials' mechanical properties as input data, in addition to some acoustic descriptors. Since many wood species with different mechanical characteristics can be used to manufacture CLT structures, an easily implementable non-destructive procedure to evaluate the elastic and stiffness properties would be beneficial for a straightforward characterization of specific CLT building elements. The literature offers a variety of different approaches to experimentally investigate the mechanical properties of solid wood through non destructive tests [4]. Many of them are modal analysis-based methods [5,6], or involve ultrasound measurements [7,8]. The experimental approach presented here is based on wave propagation analysis within the audible frequency range. The flexural wave velocity can be directly evaluated by measuring the time-of-flight difference between two adjoining transducers in line with the excitation source, a technique derived from ultrasound measurements [9] and also applied for the characterization of visco and poro-elastic materials [10]. Alternatively, the structural wavenumber can be determined by measuring the phase difference between two consecutive accelerometers, as proposed by Rindel [11] for low frequency measurements. This approach has also been applied by Nightingale [12] to study a wooden joist floor, implementing a slightly different setup in order to investigate higher frequencies. A method to compute the phase velocity, based on phase difference of the frequency response function FRF between two transducers [13], was also applied by Thwaites to detect damages in sandwich structures, other than to determine the material's elastic properties [14]. While these approaches uses continuous wave random noise excitation or impact impulses, the method to be described here involves short pulse excitation. Pulse excitation usually requires more effort during the measurement stage, since a longer time is needed to investigate a wide frequency range, compared to broadband excitation. On the other hand, it allows one to obtain accurate results with a much easier signal processing. The novelty aspect of the proposed method is represented by an analytical data fitting of the experimental wave velocity in order to diminish the number of single frequencies to be tested within the investigated band, reducing significantly the measurement time. Besides, the fitting procedure also limits the influence of the scatter in the experimental data, especially at high frequencies.

The aim of this work is to present a fast and non-destructive method to investigate the elastic and stiffness properties of particular orthotropic elements using wave propagation analysis. The dynamic behaviour of CLT plates is known to be orthotropic [15,16], therefore the elastic parameters, and the stiffness properties, are direction dependent. The wave velocity has to be evaluated for many angles over the plate surface to analyse separately the propagation along different directions. The propagation velocity of flexural waves has been measured on a three-ply cross-laminated timber plate surface for different propagation angles, instead of cutting beams along those directions [17]. Consequently, due to its non-destructive nature, the method can be applied either in-situ or in laboratory. The study was motivated by the necessity to investigate the vibro-acoustic behavior of CLT plates. In structural design CLT elements are generally treated as multilayered structures, or composite liminates, and analysed using advanced plate theories [18]. Even though elementary Kirchhoff's or Mindlin's theories, might not be enough accurate for structural analysis of CLT plates and higher order approach are necessary, they allow accurate approximated results when applied in vibro-acoustic modelling, since the order of magnitude of the transverse displacements induced in the structures is much smaller. An example of how they have been used to model sound radiation efficiency of a CLT plate can be found in [19]. In the next paragraph the dispersion relation for flexural waves propagating in a plate is introduced, highlighting the differences between Kirchhoff's classical thin plate theory and Mindlin's theory for thick plates. In Paragraph 3 the tested structure and the measurements setup are introduced, and the signal processing to determine the real part of the flexural wave velocity is described. The methods to evaluate the material's stiffness characteristics are presented in Paragraph 4. From the experimental wavenumbers the stiffness properties of the equivalent thin orthotropic plate have been derived. Moreover, it was also possible to evaluate the in-plane elastic constants of the orthotropic plate under Mindlin's assumptions. The main results are finally shown and discussed in Paragraph 5.

2. Theoretical background

The velocity of a flexural wave propagating in an elastic solid depends on the frequency. The wave dispersion relation can be determined from the equation of motion of the vibrating structure. There are several simplified analytical approaches to describe the dynamic response of a beam or a plate. Kirchhoff's plate theory, also known as classical thin plate theory, considers only pure bending, neglecting both rotational inertia and shear deformation effect. Under these assumptions, the equation of motion of a thin isotropic plate undergoing unforced vibration is described as a function of the transverse displacement w as [20]:

$$D\nabla^4 w + \rho h \frac{\partial^2 w}{\partial t^2} = 0. \tag{1}$$

The bending wavenumber k_B depends on the angular frequency ω, the bending stiffness of the plate D, given in Eq. (11), its density ρ, and its thickness h: