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Experimental determination of the equivalent-layer shear stiffness of CLT through four-point bending of sandwich beams

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HIGHLIGHTS

- A new test is presented to measure the equivalent layer out-of plane shear stiffness of Cross Laminated Timber.
- The bending stiffness is directly measured from the rotation at support.
- Assumptions and validity of the model are verified numerically.
- The experimental study shows promising results with a reduced measurement dispersion.

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ABSTRACT

In this paper, a new methodology for the experimental determination of the CLT equivalent cross-layer shear elastic modulus is suggested using a wooden core sandwich beam with Carbon Fiber Reinforced Polymer skins under four-point bending. The stiffness contrast between the wooden layer and the CFRP skins ensures that the bending stiffness of the sandwich beam is mostly driven by the CFRP skins and the shear force stiffness of the beam is mostly driven by the shear modulus of the wooden core. Several measurements for the determination of the bending stiffness of the sandwich beam are investigated. Particularly, it is shown that the suggested measurement of the bending stiffness from rotation at beam ends presents more reliable results than common measurements of curvature. Then the results of a preliminary experimental study are presented using this set-up and promising results are obtained: the equivalent cross-layer shear modulus is measured at 124 MPa which lies well within literature.

1. Introduction

Cross-Laminated-Timber (CLT) is a wooden product made of several lumber layers stacked crosswise and glued on their wide faces. CLT panels are classically used in walls, floors and roofs as load carrying plate elements. Because of their low self-weight, their quick and easy assembly and their low environmental impact, CLT panels have gained in popularity during the last few years in Northern America and in Western Europe. Several timber buildings made partly or entirely of CLT were built such as the Stadthaus building at Murray Grove in London [1], the Treet in central Bergen [2] and many other projects are in progress such as the Ho–Ho building in Vienna [3] and the student residence Brock Commons in Vancouver at the University of British Columbia [4].

Nevertheless, timber is a highly anisotropic material. The shear modulus between radial and tangential directions of softwood species, also called rolling shear, is two hundred times smaller than the Young modulus in the fibers direction. Because of the cross layers in CLT, the rolling shear significantly contributes to the global behavior of the CLT panel. Several recommendations are currently being developed to include these effects. The γ-method recalled in Eurocode 5 [5] was adapted to CLT [6] considering cross layers as mechanical joints between longitudinal layers having a stiffness related to the rolling shear modulus. The shear analogy method [7] models the CLT beam as two virtual beams: an Euler beam without shear deformations and a Timoshenko beam including shear stiffness of each layer. These simplified approaches may not always be sufficient for predicting the mechanical behavior of CLT and some advanced modelling are often required [8–11]. Finally, in the CLT-designer software®, Thiel and Schickhofer [12] suggest to use Timoshenko beam theory and derived the shear stiffness of the CLT beam from the [13] method. In all these

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approaches a reasonable estimate of the equivalent layer shear modulus is of importance.

Numerous approaches have been suggested to measure this modulus but they are not always reliable because of stress concentrations or because of indirect measurement of the shear modulus. Moreover, a difference was observed between the local rolling shear modulus at ring scale, measured at 50 MPa approximately for softwood species and the equivalent shear modulus at board scale which may be significantly larger [14–16]. Indeed, at ring scale, wood elastic behavior may be modeled as orthotropic with three main directions: the longitudinal direction L corresponding to wood fibers orientation, the radial and tangential directions R and T (Fig. 1). At board scale, the rotation of the material orthotropic coordinate system (O, L, R, T) generates an additional heterogeneity. Hence, the reference frame of the board is defined as (O, L, C, Z) where C and Z stand for cross and normal directions of the board (Fig. 1). From these considerations, it appears that the relevant definition of rolling shear modulus for engineering predictions of CLT plate behavior is an averaged property of the actual heterogeneity in a CLT layer which itself is made of the assembly of glued or unglued boards.

In the present paper, we suggest a new experimental approach using the four-point bending test on a sandwich beam made of a wooden core between two Carbon Fiber Reinforced Polymers (CFRP) skins. In this setup, the cross-layer of a CLT is isolated from other layers and mostly contributes to the global shear behavior of the sandwich beam. It ensures a stress state close to the actual one in CLT and a proper and relevant measurement of the equivalent layer shear modulus which is the relevant data for engineering applications. This equivalent shear modulus is denoted G_{CZ} following the reference frame of the board.

In Sections 1.1 to 1.3 several experimental studies on the shear behavior of timber are reported and classified according to the specimen scale: from the ring scale to the beam scale. After that, in Section 1.4, the suggested methodology is briefly introduced. In Section 2, the validity of the sandwich beam model under four-point bending is investigated for specimen with a wooden core and CFRP skins. A measurement of the apparent bending stiffness from the rotation at supports is suggested and compared to already existing methods. Then, the feasibility and the relevance of the methodology is validated experimentally: the protocol is shown in Section 3 and main results on Norway Spruce specimen are presented in Section 4.

1.1. Tests at the ring scale

Numerous studies have been published on the local rolling shear modulus of elasticity G_{RT} of timber using many different tests which were extensively reviewed and analyzed by Dahl and Malo [17]. In these tests, a particular attention is always paid to the relative size of specimens compared to the radius of curvature of annual rings in order to preserve a uniform orientation.

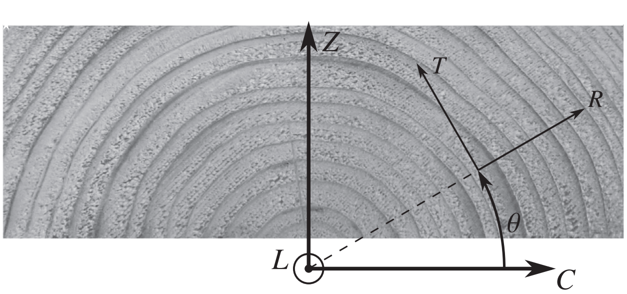

Fig. 1. Local and global orientations in a board.

The first methodology consists in compression tests on small timber blocks with geometries and loading configurations leading to a local shear state in timber. Several of them are listed by Kollman and Côté [18]. The notched shear block test suggested by the American Society for Testing and Materials (ASTM) [19] consists in the compression of a small cubic block with notches (Fig. 2). This test has been extensively used to measure shear strength of timber, some of which are reported in [18]. Nevertheless it has been criticized by many authors [17,20,21] because of three main drawbacks: it introduces high stress concentration caused by the notch, an additional bending moment is caused by the load eccentricity and the non-uniform stress distribution over the failure plane yields inaccurate strength results. Moses and Prion [22] captured these effects by a finite elements model and observed that they lead to an underestimation of the shear strength by a ratio of 1.7 approximately. A comparable test method called short beam tests consists in a beam with a very small span to depth ratio uniformly loaded. Dahl and Malo [17] observed improper failure due to additional bending moment and to impure stress state.

Another configuration is called the Iosipescu shear test [24]. A beam with 90° notches at top and bottom of the central section is loaded such that the central section is under pure shear stress. Using this method, Dumail et al. [25] measured an average rolling shear modulus of 57.7 MPa on specimen made of *Norway Spruce* where the variations of ring orientation were negligible. Nevertheless, because of the bending moment close to the central section, the shear failure can be affected by improper failure particularly in the radial-tangential plane.

Using a comparable mechanical principle, the Arcan shear test [26] consists in loading specimens with a butterfly shape, which is intended to generate pure shear failure at the center section (Fig. 2). Dahl and Malo [17] used this test in six different configurations to measure the shear modulus in the three orthotropic directions and evaluated an averaged rolling shear modulus of *Norway Spruce* equal to 30 MPa approximately using video extensometry. In a following study, Dahl and Malo [27] measured an average rolling shear strength of 1.6 MPa. From these results, Dahl and Malo [17] observed that the Arcan shear test seems one of the most

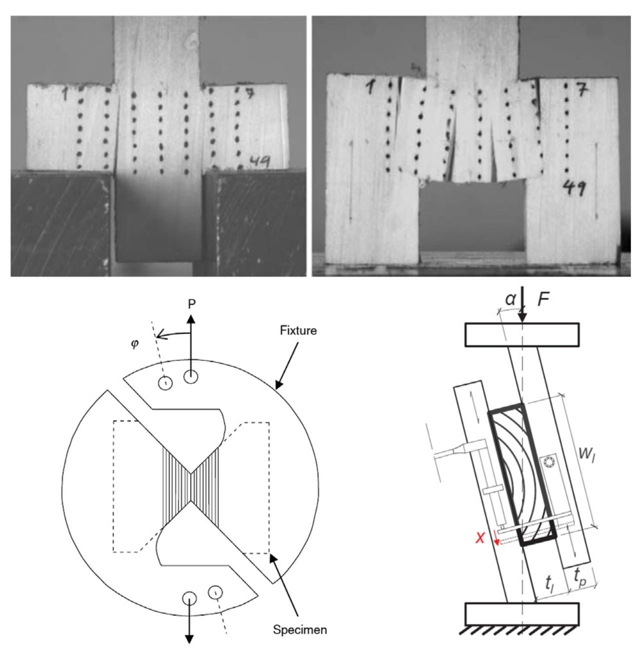

Fig. 2. Notched shear block test [17] (top), Arcan shear test [17] (bot. left) and Single-lap shear test (bot. right) [23].