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General shell section properties and failure model for cross-laminated timber obtained by numerical homogenization

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ABSTRACT

In this study homogenized mechanical properties are derived for structural finite element analysis of cross-laminated timber (CLT) discretized by means of shell elements. In the first step, based on the results of experimental three-point bending tests on a CLT slab component, a numerical optimization procedure is applied to identify the elastic and plastic properties of the individual spruce wood laminates, considering orthotropic elasticity and Hill's yield criterion. Taking into account its periodic structure, a repeating unit cell (RUC) of the CLT is defined in the subsequent step. To this RUC specific loading conditions are imposed successively, yielding the entries of the homogenized elastic stiffness matrix of a general shell section. Extending the RUC simulations into the inelastic domain of deformation results in a homogenized failure surface on the structural scale, which is implemented as a postprocessing variable in a commercial finite element program. Throughout all analyses, in sensitivity studies the most decisive material properties are identified. Results of comparative simulations on a homogenized structural model and an elaborate full three-dimensional finite element model of a point-supported CLT slab show the accuracy and efficiency of the proposed approach based on homogenized mechanical properties.

1. Introduction

Cross-laminated timber (CLT) is a panel-like structural component, composed of several perpendicularly arranged wood laminates glued on the wide faces. Typically, three, five or seven lumber layers form a CLT panel of 10–30 cm thickness. In buildings CLT panels are used as load-bearing wall and floor elements. Main advantages of CLT over other structural timber products are its dimensional stability and biaxial load transfer capability. CLT has been used in timber engineering since the nineties of the last century [1], and more recently it has become a competitive component in structural engineering, representing an alternative to reinforced concrete and masonry structures with a high degree of prefabrication potential [2].

Increased application of CLT as structural component with larger span in taller buildings requires more sophisticated methods of structural analysis to predict sufficiently accurate its serviceability (deformation and vibration behavior) and load-bearing capacity. The main contribution of the present paper is a novel method for the determination of a set of appropriate homogenized mechanical properties of CLT on the structural scale, which facilitate the goal of both efficient and accurate structural analysis of CLT panels in the framework of finite element (FE) analyses. However, before CLT can be modeled satisfactorily for such analysis, it is important to understand the mechanical behavior of the individual wood lamina.

It is generally accepted that wood is an orthotropic material in its elastic range of deformation [3]. The elastic mechanical properties at each point are different along three mutually perpendicular principal axes, which coincide with the axial direction (along the grain), the radial direction, and the circumferential direction. The two latter directions are oriented with respect to the growth rings, and thus, the principle axes define a cylindrical coordinate system. Mechanical properties, such as stiffness and strength, in axial direction ("along the grain") are considerably larger than those in the radial and circumferential directions ("across the grain"), thus representing approximately transverse isotropic behavior. For instance, Young's modulus along the grain is typically 10–100 times larger than across the grain. Hofstetter et al. [4] were able to explain the effect of lumen porosity and water volume fraction on the elastic properties of wood. Their study is based on a four-step homogenization procedure, starting on the nanometer scale with a polymer network consisting of lignin, hemicellulose, water and extractives. Additionally to density and moisture, also the presence of defects, such as knots and resin pockets, has a pronounced effect on structural properties of wood, particularly on its strength [5,6]. In contrast to its elastic orthotropic behavior, wood in the inelastic range

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of deformation is highly anisotropic, as shown in experimental studies [7]. For instance, the post-yield load-deformation path in compression is very different from that in tension. Consequently, in terms of computational plasticity advanced material models should be employed, for example in the framework of multi-surface plasticity, to predict numerically the inelastic response of wood [8–10].

On the structural scale, CLT can be characterized as a shear-compliant multilayer panel composed of thick cross-wise disposed orthotropic layers, whose transverse shear stiffness differs layer-wise by a factor of about 10. The resulting discontinuous deformation across the CLT thickness with kinks at the interfaces is, thus, primarily governed by the shear modulus across the grain. Related to this behavior is the so-called "rolling shear" failure, which typically occurs in slabs with smaller spans and in point-supported slabs [11]. Additionally, interlaminar bonding (rigid versus flexible bond) and the position of relief notches affect the structural behavior of CLT, thus, making the numerical prediction of failure loads a challenge.

In the most general approach of structural analysis, a three-dimensional FE model of the CLT component is built, which captures the mechanical properties of the individual wood laminates and the interface conditions. Numerical analysis based on such a model exceeds, however, the capacity of computers used in engineering practice by far, and can only be conducted on computer clusters usually not available in design offices. Furthermore, time-consuming elaborate modeling is required.

Since CLT components represent two-dimensional panels, in most cases plate theories can be used to predict numerically the global mechanical behavior on a structural scale. Application of those theories reduces the computational effort significantly to an order of magnitude accessible to computers available in design offices. The cross-wise disposal of the wood layers makes CLT a strongly inhomogeneous building component, whose mechanical behavior can only be captured by means of laminate plate theories. Extensions of homogeneous shear-deformable plate theories to composite plates lead to layer-wise theories and equivalent single-layer theories, as discussed in [12,13]. For instance, the equivalent single layer theory developed by Murakami [14] reproduces the zig-zag shaped deformation pattern specific to laminated panels such as CLT based on seven deformation variables. Another theory of this kind with seven independent kinematic variables is proposed in [15]. The comparative study of Stürzenbecher et al. [16] shows that the latter theory delivers for CLT panels the closest prediction of analytic reference solutions. While the first class of theories allows to predict layer-wise stress state and deformation, equivalent single-layer theories can only predict deformation and load-bearing capacity of composite plates globally. Structural analysis based on equivalent single-layer theories is much more efficient because a smaller amount of kinematic variables needs to be defined, and thus, it is preferred in engineering practice. Its application, however, requires a set of homogenized structural parameters. A review on mechanical models for layered panels and shells is provided by Noor et al. [17]. A series of papers deals with wooden composite beam and plate structures (e.g. [18–22]), where rigid bond between the layers cannot be achieved. However, modeling of this effect in CLT panels is out of scope of the present study. More recently, Saavedra Flores et al. [23] conducted multi-scale FE analyses to derive homogenized structural properties for CLT. They considered three scales of lumber, i.e. the scale of microfibrils, the scale of wood cells, and the structural scale of CLT panels. Defining random variables for micromechanical properties, experimentally obtained macromechanical properties such as density, Young's modulus and other stiffness parameters of CLT could be validated theoretically.

In the present contribution, a different approach is used to derive a set of homogenized mechanical properties that reproduces deformation and load-bearing capacity of CLT in terms of shell FE analysis on a structural scale. Taking into account the periodic lay-up of CLT, a representative unit cell (RUC) of CLT on the macroscopic level is defined. To this RUC a numerical homogenization procedure is applied, resulting in mechanical parameters for shell elements readily implemented in commercial FE software packages.

Recently, this approach has been applied for CLT homogenization also by other authors. Silly [24] conducted extensive numerical studies to obtain information on the effective torsional and in-plane shear stiffness of CLT panels. Based on these outcomes, stiffness reduction factors were derived for CLT with three to seven layers, taking into account perfect bonding of the narrow faces as well as gaps between the narrow faces of the individual boards, as it is often observed in CLT. Homogenization of thin and thick CLT plates are addressed comprehensively in [25], proposing the so-called Bending-Gradient theory for laminated plates, which is an extension of the classical Reissner-Mindlin theory for homogeneous thick plates. In this theory, instead of two independent shear forces and corresponding degrees of freedom, a generalized shear force third order tensor with six degrees of freedom is introduced. Franzoni et al. [26] applied this theory to investigate the influence of gaps between the narrow faces of CLT panels on in-plane shear, torsional and transverse shear stiffnesses. Typically, there is a distinct stiffness reduction once a gap of any width is present when compared to a setup without gap. Based in the comparison of the transverse shear stiffnesses predicted by the Bending-Gradient theory and the Reissner-Mindlin theory, they found that the latter theory yields accurate results except for the considered three-ply lay-up of CLT.

Nonlinear effects, such as inelastic behavior and opening or closure of joints, as well as defects, such as knots, can be integrated in the RUC, thus, rendering numerical homogenization a versatile utility. The procedure adapted for this study was originally developed for numerical homogenization of brick masonry [27,28]. The presented extension for CLT, however, also captures transverse shear deformations. The derivations of the present study are based on a CLT panel composed of five layers of spruce boards. Application to CLT with different number of layers and different dimension is, however, straight forward. Original contributions in this paper are the application of numerical homogenization that delivers a general shell stiffness matrix for CLT in terms of FE analysis, the derivation of a failure surface for CLT based on numerical homogenization, and the verification of the proposed homogenized mechanical properties on the example problem of a large scale point supported CLT plate.

2. Experimental studies

In the first step, in the laboratory (TVFA) of the Department of Engineering Sciences at the University of Innsbruck the load-displacement curves up to failure of a set of CLT test specimens made of spruce wood laminates were experimentally determined. These outcomes serve as basis for subsequent numerical identification of the mechanical properties of the utilized spruce wood and the interface conditions. Each tested CLT specimen of 110 cm length, 30 cm width and 10 cm thickness is composed of five wood layers, 17 cm wide and 2 cm thick each. The wood boards are glued on the wide faces, whereas the contact zone at the narrow faces remains without glue. Three different setups as shown in Fig. 1 were subjected to quasi-static three-point bending tests, resulting in total in six experiments because two different specimens of each setup were tested. In the first configuration, the grains of the faces and the central layer are in parallel to the main load transfer direction, while the fibers of the second and fourth layer are cross-wise arranged, referred to as 0° configuration. The second configuration is composed of cross-laminated layers with ± 45° fiber orientation with respect to the longitudinal axis. In the third 90° configuration the second and fourth layer are longitudinally oriented. During the tests, the force applied via a hydraulic cylinder was recorded by a load cell attached to the hydraulic cylinder, and two inductive displacement sensors measured the mid-span deflection left and right of the cross-section through steel plates attached to the central laminate. Fig. 2(a) shows the test setup for the 0° specimen.