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Numerical study of cross-laminated timber beams using Hill's yield criterion

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Abstract
The computer simulation of wood-based products poses a challenge for professionals in the area, as it is a material with anisotropy, whose properties vary according to the species. Among the wood-based composites is CLT (Cross-laminated Timber), manufactured with lamellae arranged in crossed layers and generally used as an element of walls, slabs and floors. The aim of this work was to analyze the stress distribution in numerical models of CLT beams subjected to three-point bending. Three types of constitutive models were evaluated: the linear isotropic; linear orthotropic; and orthotropic with physical nonlinearities, which is obtained with bilinear curves by Hill's yield criterion. The validation of the numerical models was performed from the experimental load-deflection curves of CLT beams made with *Eucalyptus grandis* and *Toona ciliata* (Australian Cedar) loaded until failure. For the simulations, the ANSYS software was used, and the constitutive values of the models were determined from the properties of each lamella. It was concluded that the orthotropic model with physical nonlinearity was closer to the experimental results due to the plastic deformation of the beam. The highest values of von Mises stresses were concentrated at the supports and at the point of application of the load for the Australian Cedar beam, while the stresses were higher in the inner layer of the Eucalyptus beam, due to the rolling shear effect. From the numerical simulation, it was possible to justify the failure modes obtained experimentally.

Keywords
Cross Laminated Timber (CLT) — Finite element method — Rolling shear — Bending — Timber structures

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1. Introduction

Cross Laminated Timber (CLT) are high strength plate /beam element manufactured of adjacent wood lamellae in an odd number of layers, commonly used in construction as wall and floor elements (Jeleč, Varevac & Rajčić, 2018; Brandt, Wilson, Bender, Dolan, & Wolcott, 2019). The development of CLT started in the 1990s in Europe, but its large-scale production took about 20 years to occur (Muszynski, Hansen, Fernando, Schwarzmann & Rainer, 2017). This material has gained attention in the 21st century due to its low carbon footprint, renewability, low weight compared to traditional construction materials and short construction period (Nie, 2015).

The mechanical behavior of CLT is complex due to the orthogonality of the fiber direction of the consecutive layers, non-uniform stress distribution and wood anisotropy (Li, 2015). Thus, when a CLT beam is bended out of the plane, the effect of shear occurs in the orthogonal oriented layers, generating the effect known as rolling shear (Ehrhart, Brandner, Schickhofer & Frangi, 2015), which causes brittle failure in wood, as a combination of shear and tensile stresses perpendicular to the fibers (Li, 2015; Nie, 2015).

It is possible to observe the stresses distribution on a bended CLT beam through numerical simulation, in order to identify which region has stress concentration. Martínez, Martínez, Rabanal and Díaz (2018) attribute the small number of numerical studies developed with CLT to the complexity generated by the orthotropy of the material. In general, computational modeling enables the numerical reproduction of the behavior of CLT elements, especially in order to prevent structural damage (Molina, 2008; Flores, Saavedra & Das, 2015; Betti et al., 2016).

Regarding the yield criteria adopted for wood in the numerical simulations, the ideal would be considering material orthotropy, resistance asymmetry (different behav-

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iors in tension and compression) and damage mechanics for the material; however, most numerical analysis software's were not designed for wood elements simulations and does not provide every yield criteria in its internal libraries. Nicolas (2006) states that several yield criteria could be applied to wood simulations, such as Norris, Hill, Hoffman and Tsai-Wu's criterion.

Hill's yield criterion is an extension of von Mises' criterion (maximum distortion energy criterion) which considers the anisotropy of materials, cold hardening and different plasticizing stresses in the three orthogonal directions (Molina, 2008). Hill's yield criterion is usually applied in numerical simulation of wood, even if its applications does not consider different values of tensile and compressive strengths (Dias, 2005; Molina, 2008).

The present study aimed to propose a numerical model, using the Hill yield criterion, to analyze the stress distribution in CLT beams subjected to three-point bending and compare failure modes with the experimental results.

2. Materials and Methods

The wood species used in the manufacture of three layer CLT elements were *Eucalyptus grandis* (413 kg/m³) and *Toona ciliata* (locally known as Australian Cedar) (357 kg/m³), both hardwoods acquired from a timber company located in the city of Riberão Branco/SP - Brazil. Jeleč et al. (2018) recommend the study of hardwood CLT since most rolling shear tests are conducted on European softwoods.

The tree-point bending test was based on the methodology described by ASTM D198 (2015), where loading was applied to the CLT beam in a single cycle until its failure at the loading rate of 4.5 mm/min. The test pieces had 110 mm width and 75 mm height, with a span of 450 mm. The internal lamellae had a 120 mm width. The use of a span equivalent to six times the height is justified by the shear stresses generated in the inner layer of the CLT (Santos, 2016).

Each lamellae had its mechanical properties determined according to ABNT NBR 7190-2 (2022) (*i.e.* compressive strength parallel to the fibers, modulus of elasticity parallel to the fibers and tensile strength normal to the fibers). These properties values were included in the numerical models for each one of the CLT beams evaluated.

The numerical study was developed on ANSYS software, based on the Finite Element Method (FEM), which was chosen due to the need for studies of this nature in Brazil (Flores et al., 2015; Li, 2015; Nie, 2015; Betti et al., 2016; Flores, Saavedra, Hinojosa, Chandra & Das, 2016) and the possibility of analyzing models in a regime of physical and geometric non-linearity.

The numerical study was divided into three stages: Pre-processing; Processing; and Post-processing. Pre-processing consisted of determining the type of finite element, mesh generation, material properties attributions and essential boundary conditions. In attributing the properties to the lamellae we chose to use SOLID45, as it is a first-order isoparametric element with eight nodes and three degrees of freedom, which allows us to adequately represent the orthotropic properties of wood and its plasticity (Molina, 2008; Flores et al., 2015; Nie, 2015; Betti et al., 2016).

A three-dimensional model was constructed and each wooden lamella was meshed separately, so that the nodes at the interfaces of the layers were coincident. We introduced gaps in the inner layers (central lamellae), as shown in Figure 1, with the entire mesh generated in the ANSYS itself. The meshes of the wooden lamellae were regular hexahedral elements with the same dimensions in the three orthogonal directions (x, y and z) of the ANSYS.

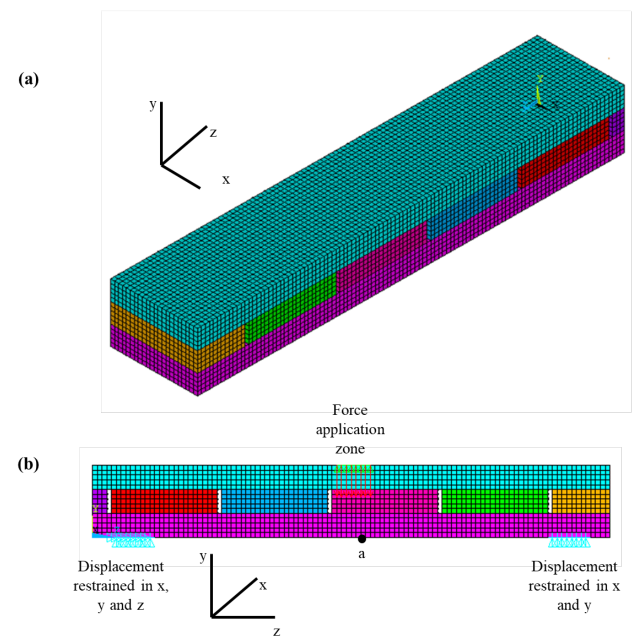

Figure 1. (
a) Mesh of the numerical model; (b) Simulation boundary conditions.

We tested three levels of mesh refinements using finite elements of 10 mm, 5 mm and 2.5 mm side. After evaluating the mesh densities, the models that used 5 mm elements were chosen due to a better approximation with the experimental results when compared to the model that used the 10 mm mesh and due to the lower computational effort when compared to models with 2.5

mm elements.

The relationships between the properties of elasticity and strength adopted for the models were based on Molina (2008). In modeling the external lamellae of the models, the orthogonal directions admitted were: x direction (tangential); y direction (radial) and z direction (longitudinal); while the lamellae of the central layer of the CLT element were: x (longitudinal); y (radial) direction and z (tangential) direction.

There were two simulation approaches, first using an orthotropic linear model and secondly considering the orthotropic plastic properties, through Hill's yield criterion. Bi-linear curves simulated the elastic-plastic behavior of wood.

The simulation boundary conditions admitted in the numerical models were coincident with those used in the experimental tests. The upper central nodes of the beam received the load equivalent to the ultimate load obtained in the experimental tests. To avoid convergence problems, the upper nodes where the loads were applied (Figure 2b) were coupled so that they all had the same amount of vertical displacement.

The loads were applied in 1 load step for the linear models and in 60 load steps in the nonlinear simulations. To ensure that the coincident nodes, from different lamellae, displaced together, we include the command "NUMMRG". These actions were necessary to ensure the convergence of the nonlinear numerical model; all other simulation parameters were adopted according to ANSYS standards (*e.g.* convergence parameters and resolution methods).

After the pre-processing stage, the next numerical step was carried out, where the software generated the linear systems and solved the respective equations. The results were validated according to the load x displacement curves obtained in the experimental tests. For that, the displacement of the central node located in the lower layer (Figure 2b, point a) was compared to the displacement measured with the LVDT transducer in the experimental tests (Figure 1).

3. Results and Discussion

For the numerical models analyzed (*E. grandis* and *T. ciliata*) the "load" versus "displacement" curves were analyzed to the point of maximum convergence of the results (with a tolerance of 0.001) and compared to the experimental curves obtained experimentally. The stresses distributions analysis was performed for the non-linear simulations, because the values obtained were closer to those measured experimentally.

The failure mode observed experimentally in the bending tests of the *E. grandis* CLT beam was shear/tension (see Figure 2b) in the central layer of the specimen. These failures were the result of a combination of stresses, shear stress and tension perpendicular to the fibers, in an inclined direction in relation to the horizontal axis of the central lamella. This failure mode (rolling shear) occurred by inclined traction associated with rolling shear with a rupture angle between 35º and 50º, as seen in Nie (2015) and Li (2015). As observed in the von Mises stress distribution (Figure 2a), there was a concentration of stress in the lamellae of the inner layer in the thirds of the span, exactly where wood rupture occurred.

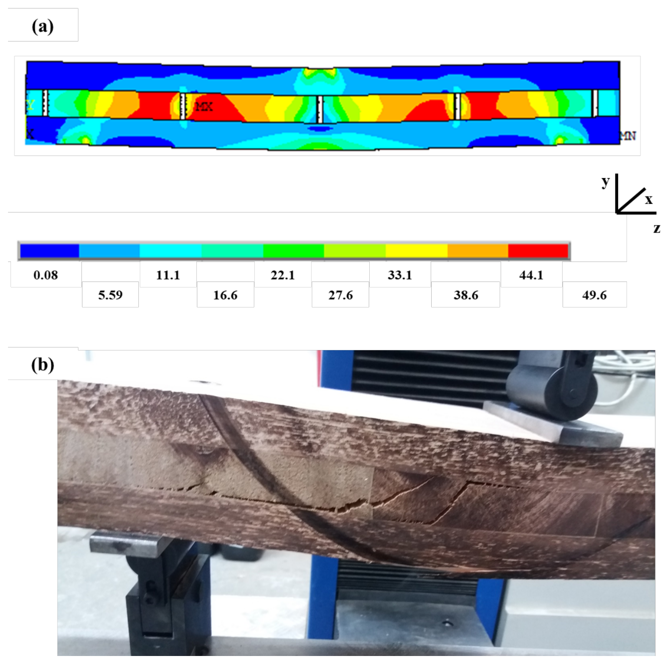

Figure 2.

(a) Von Mises stresses distribution of the *E. grandis* beam (in MPa); (b) Experimentally obtained failure mode.

The second failure mode, that occurred in CLT beams made of *T. ciliata* wood (Figure 3b), was a mixture of normal crushing normal to the fibers in the region of load application and failure at the bottom layer due to tension parallel to the fibers. From the von Mises stresses distribution (Figure 3a) it is possible to observe the stress concentration in the load application regions and in the lower central region of the lower layer of the CLT. It is important to point out that the load application area in this numerical model was the same as the area occupied by the metal plate in contact with the specimen under test, whose width did not exceed half the thickness of the specimen (Santos, 2016).

The failure mode obtained for the *T. ciliata* species can be justified by the lower density of wood compared to *E. grandis*, so that the upper lamella suffered locally indentation before the inner layer lamellae failed due to

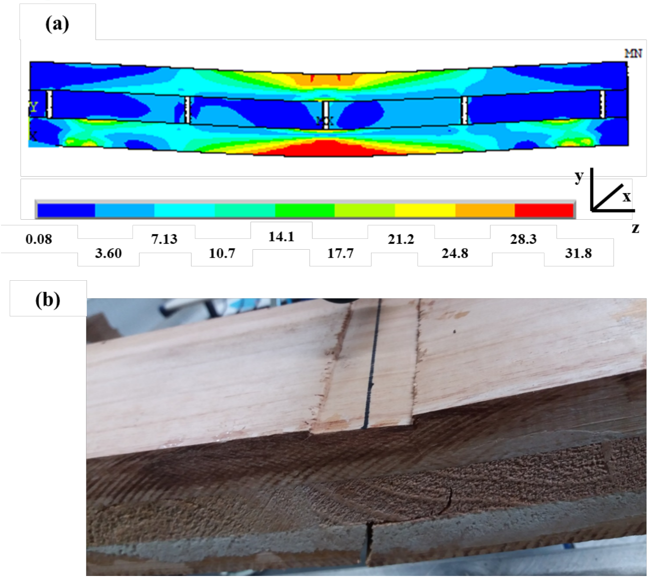

Figure 3.
(a) Von Mises stresses distribution of the *T. ciliata* beam (in MPa); (b) Experimentally obtained failure mode.

rolling shear. Thus, the bending method have limitations for the characterization of the rolling shear strength and stiffness because the failure mode was dependent on the wood species.

Ehrhart et al. (2015) state that the stresses values supported by CLT are proportional to the density of the wood, and this fact was also observed in the present work since *E. grandis* CLT showed higher values and apparent density at 12% moisture content in comparison to the *T. ciliata* CLT. The same order of magnitude of stresses obtained was also observed in both tests, indicating good correspondence between numerical and experimental methods.

The numerical models proposed considering orthotropy (different elastic and plastic properties for the three orthogonal directions of the wood) were capable of simulating, with relative approximation, the behavior of the bending specimens. This was observed for the linear and non-linear phases as the stress distributions allowed a better understanding of the observed experimental failures.

Even though wood have different properties and behaviors in tension and compression, the Hill's yield criterion was able to identify the zone of von Mises stress concentration. Also, it is worth mentioning that the finite element SOLID45 is a very simple and rigid element that only considers the elastic and plastic properties of wood. In this case, no matter how much the mesh was refined, no significant improvements were obtained in the model response.

4. Conclusions

The methodology applied to the simulation of CLT beams was adequate to analyze the specimens, showing good correspondence to the experimental failures obtained. Also, the hill's yield criterion was able to numerically represent the behavior of the hardwood species evaluated. Other yield criteria could be implemented into the software to enable the comparison of different methods on the final stress distribution of the samples.

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