A computational approach for the modelling of rolling shear cracks in

cross-laminated timber structures

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Abstract

This paper addresses the computational modelling of rolling shear cracks in cross-laminated timber structures. In order to predict the structural response, four spatial scales are interlinked within a multi-scale modelling framework. Material information is taken from the wood cell-wall at the order of few nanometers, wood fibres with dimensions of some micrometers and growth rings described by a few millimeters. A computational homogenisation scheme is adopted to determine the effective mechanical properties at each scale. The homogenised mechanical properties are then used to analyse the fourth (structural) scale represented by a cross-laminated timber plate with dimensions of the order of the meter. In order to simulate the cracking in the material, a cohesive zone model is adopted at the homogenised macroscopic scale. This approach allows us to model interlaminar and inter-fibre cracks. Our numerical simulations reveal the potential predictive capabilities of the present approach to investigate further wood and other natural materials.

Keywords: Cross-laminated timber, Rolling shear cracks, Multi-scale modelling

Introduction

Cross-laminated timber (CLT) consists of structural panels made up of several layers of boards stacked crosswise and glued together on their faces. Among its main advantages, we can highlight its favorable seismic performance, its ability to self-protect against fire and its excellent strength, which allows wood to be used in tall buildings with heights up to 30 stories [Fairhurst et al. (2010)].

One important issue in the design of CLT structures which still requires further investigation is the rolling shear failure [Zhou et al. (2014)]. It consists of inter-fibre cracking due to shear strains in the plane perpendicular to the longitudinal axis of the wood fibres. Figure 1 shows a typical rolling shear failure found in the central layer of a CLT plate subject to out-of-plane loads. In particular, the design of CLT floor systems with low span-to-depth ratios is often governed by the rolling shear capacity of CLT plates and therefore, its full understanding is of paramount importance to prevent damage in CLT structures.



Figure 1: Typical rolling shear failure in a CLT plate subject to bending

In order to capture rolling shear cracking in a CLT plate, we propose in this paper a modelling strategy which combines the use of a homogenisation-based multi-scale modelling framework to determine the undamaged mechanical properties of wood, and the adoption of cohesive interfaces at the homogenised macroscopic structural scale to model the crack behaviour.

In the context of multi-scale modelling of CLT structures, few attempts have been made in order to predict the CLT structural response [Saavedra Flores et al. (2014); Saavedra Flores et al. (2015a; 2015b)]. We note, however, that despite the increasing interest in this subject, the complete understanding of the mechanical properties of CLT is still an issue which remains open at present. In this new paper, we continue with the line of development started in the above references [Saavedra Flores et al. (2014); Saavedra Flores et al. (2015a; 2015b)] by presenting new numerical results.

Computational approach

In the present paper, we adopt a homogenisation-based multi-scale constitutive framework in which each material scale is associated with a microstructure whose most statistically relevant features are incorporated within a representative volume element (RVE). This RVE is assumed to have a (microscopic) characteristic length much smaller than the macro-continuum, and at the same time, a size large enough to capture the microscopic heterogeneities in an averaged sense.

In this theory it is assumed that the macroscopic or homogenised strain tensor at any arbitrary point of the macroscopic continuum is the volume average of the microscopic strain tensor field over the domain of a representative volume element of material (RVE). Similarly, the macroscopic or homogenised stress tensor field is assumed to be the volume average of the microscopic stress tensor. This multi-scale framework is adopted to find the homogenised constitutive response at each material scale. In wood, these scales are represented by the wood cell-wall at the order of few nanometers, the wood fibres with cross section dimensions of tens of micrometers, and the growth rings described by some few millimeters. For further information about the morphology and composition of wood at the nano- and microscopic scale level, we refer, for instance, to [Dinwoodie (1981)]. The homogenisation of these three (material) scales (represented by three different RVEs) allows us to predict the response of the fourth (structural) scale, that is, the CLT plate.

The main philosophy behind the present multi-scale strategy is to start from the response of very basic (but fundamental) ingredients at small scales and then, build up an increasingly complex and intricate response as the length scale increases. We note here that the determination of an accurate prediction of this response would (probably) be unfeasible by means of conventional phenomenological models.

As we are interested in modelling cracking in the material, we adopt a Cohesive Zone Model (CZM) at the macroscopic structural scale. CZM is the simplest model that allows to describe in full a fracture process (i.e. initiation and propagation of the crack) and has been thoroughly used to treat several materials such as concrete, rocks, fibre-reinforced plastics and wood [Allix et al. (1998); Elices et al. (2002), Saavedra et a. (2012)].

The basic idea of the CZM can be described as a zero thickness interface transferring tractions which are related to the displacement jump of the interface [u] by the meaning of a softening function. This evolution law can be written in terms of a damageable stiffness operator k([u]). At the beginning, the interface stiffness has no damage (k_0) . Then, the stiffness decreases with respect to the displacement jump and becomes zero at some critical displacement jump. It is possible to use a damage variable *d* to represent the stiffness of the interface, i.e., $k = (1-d)k_0$, with *d* ranging from 0 (healthy interface point) to 1 (completely damaged interface point). The area under the entire stress-displacement jump curve is the energy per unit area G_f [J/m²] necessary to separate completely the interface at a given point.

Numerical simulations

This section describes the numerical results obtained by the present multi-scale approach enriched with macroscopic cohesive laws. The CLT specimen consisted of three 4-cm-thick layers with a length of 75 cm and a width of 39 cm. The span length between supports was 60 cm. The outer layers were made up of timber pieces oriented in the strong direction of the panel. The central layer was made up of members oriented in the weak direction. Edge-gluing is considered between the opposite sides of adjacent layers. The macroscopic finite element mesh consists of 861696 linear wedge elements and 2.9 millions of DOFs (because of the symmetry of the problem, only one quarter of the geometry is considered). Further details on the finite element models of the RVEs associated with the corresponding sub-scales can be found in [Saavedra Flores et al. (2015b)]. Cohesive interfaces are used to simulate the rolling shear failure, but a distinction between the interlaminar interfaces (for delamination) and the inner interfaces of the central layer (for inter-fibre cracking) is made. When a cohesive interface is completely delaminated, contact conditions are considered to avoid interpenetration.

Figure 2 shows the computational simulation of the rolling shear failure in the CLT plate subject to three-point-bending. The corresponding contour plot shows the principal stresses. In our simulation, two parallel cracks are predicted consistently with experiments (not detailed here), along with some delaminated regions, mainly between the bottom and central layer. In our numerical predictions, we note that after a cohesive interface has become fully damaged, it is converted into a contact interface as well.



Figure 2: Computational simulation of rolling shear failure in a CLT plate subject to bending

Furthermore, our model predicts a critical load of 160000 N when the first crack starts propagating in the material, which coincides with the critical value obtained during the experiment.

Conclusions

This paper has addressed the modelling of rolling shear cracks in CLT plates subject to three-pointbending. Micromechanical information coming from three scales have been taken into account in order to compute the effective material properties for the analysis of the structural scale. Cracking has been captured by introducing macroscopic cohesive interfaces in the model. The proposed approach has been able to capture key features in the rolling shear failure of CLT plates, revealing the potential applications of our approach on the study of CLT structures under different configurations of layers and loading conditions.

Finally, we remark that studies are currently under way to explore the buckling behavior and buckling-delamination interaction in CLT walls under compressive loads. This will be the subject of a future publication.

Acknowledgments

E.I. Saavedra Flores acknowledges the financial support from the Chilean National Commission for Scientific and Technological Research (CONICYT), FONDECYT REGULAR research project No 1140245.

K. Saavedra acknowledges the financial support from CONICYT, FONDECYT Initiation into Research project No 11130623.

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