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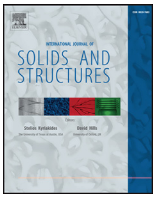

Multi-scale modelling of rolling shear failure in cross-laminated timber structures by homogenisation and cohesive zone models

E.I. Saavedra Flores[a], K. Saavedra[b,*], J. Hinojosa[b], Y. Chandra[c], R. Das[d]

[a] Departamento de Ingeniería en Obras Civiles, Universidad de Santiago de Chile. Av. Ecuador 3659, Estación Central, Santiago, Chile
[b] Departamento de Tecnologías Industriales, Universidad de Talca, Los Niches km 1, Curicó, Chile
[c] College of Engineering, Swansea University, Singleton Park, Swansea SA2 8PP, United Kingdom
[d] Department of Mechanical Engineering, University of Auckland, Auckland 1010, New Zealand

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ABSTRACT

In this paper we investigate the rolling shear failure in cross-laminated timber structures by homogenisation and cohesive zone models. In order to predict the structural response, four spatial scales are interlinked within a purely kinematic multi-scale modelling framework. The constitutive description has incorporated information coming from the wood cell-wall in the order of a few nanometres, wood fibres with dimensions of tens of micrometres and growth rings described by a few millimetres. The computational homogenisation scheme is solved sequentially from the lowest to the highest level in order to determine the effective mechanical properties for the fourth (structural) scale represented by a cross-laminated timber plate with dimensions of the order of one meter. In order to simulate the cracking in the material, a cohesive zone model is adopted at the homogenised macroscopic scale. The finite element problem is then solved using a mixed domain decomposition strategy due to its huge number of unknowns. This approach allows us to capture interlaminar and inter-fibre cracking and to solve the macroscopic equilibrium problem using parallel computations. Our numerical predictions are compared with experimental results and are validated successfully. In particular, we study the influence of wood density, edge-gluing and span-to-depth ratio on the rolling shear failure in cross-laminated timber.

1. Introduction

Over the last few years, cross-laminated timber (CLT) has been increasingly spreading in the construction sector as a new prefabricated building system. 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 fast and efficient on-site installation, its favourable seismic performance, its ability to self-protect against fire and its excellent strength, which allows wood to be used in never before seen buildings, with heights up to 30 stories (Fairhurst et al., 2010).

In spite of the above advantages, and the considerable growth that the total production is experiencing in the world market (Brandner, 2013), engineers are still far from exploiting the maximum potential of CLT structures. In this context, different methods have been proposed to design them. However, to date no method has been universally accepted by CLT manufacturers and designers (Gagnon and Pirvu, 2011). Due to the complexity of wood mechanics, many timber design rules are still based on an empirical background, resulting in conservative design procedures with unnecessarily high factors of safety.

The difficulties to fully understand the mechanics of wood materials lie mainly in their hierarchical microstructure distributed across several length scales, from sub-micrometre dimensions to macroscopic levels (Haldar and Bruck, 2013; Saavedra Flores and Friswell, 2012). In the context of wood materials and new wood-inspired composites (Haldar et al., 2011; Stanzl-Tschegg, 2011), this important feature has been subject of intensive research over the last few years by means of homogenisation-based multi-scale modelling techniques (Holmberg et al., 1999; Rafsanjani et al., 2013; 2014; Saavedra Flores et al., 2015; Saavedra Flores and Friswell, 2012; 2013).

The above multi-scale modelling framework has proved to be successful in capturing non-linear response of difficult representation by means of conventional internal variable-based phenomenological models. One of its major achievements has been the possibility to describe the ductile structural failure characterised by hardening plasticity, that involves large amounts of plastic work and non-linear geometric effects of finite strain, and that ends with

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[*] Corresponding author. Tel.: + 56 75 2201787.
E-mail address: ksaavedra@utalca.cl, ksredlich@gmail.com (K. Saavedra).

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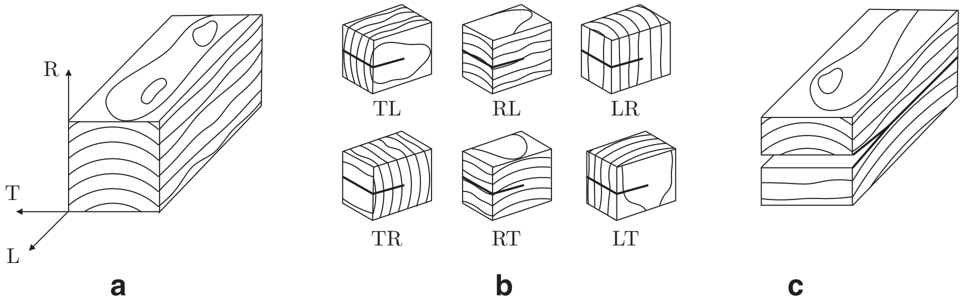

Fig. 1. a) Principal axes of wood; b) fracture systems (the letters give the normal direction to the crack plane and the direction of propagation, respectively) (de Moura et al., 2010) and c) delamination between two adjacent CLT layers (interlaminar cracks).

a sharp fracture. In this context, there is no dispute that the multi-scale approach is realistic, delivering to the continuum macro-scale essential information on the physical behaviour of the sub-scale (Bažant, 2007).

If, on one hand, such models offer the possibility to describe accurately the response of solids that involve a stable microscopic constitutive behaviour, on the other hand they fail to predict the mechanical response when progressive softening damage is present in the material. Conventional multi-scale approaches represent a reliable predictive tool only if the material is hardening, but not if it exhibits phenomena such as fibre and inter-fibre cracking, delamination, buckling of fibres or delamination-buckling interaction, among other effects.

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, that is, the *L*-axis shown in Fig. 1a. In the same figure, the axes *R* and *T* denote the radial and tangential direction of wood, respectively.

In order to characterise the fracture systems in wood materials, we follow the nomenclature (de Moura et al., 2010) of two letters (TL, RL, LR, TR, RT or LT) shown in Fig. 1b. The first letter represents the direction normal to the crack plane and the second letter the expected crack growth direction. In the rolling shear failure, the crack propagation is in the TR or RT fracture systems. We note, however, that the crack path generally changes to delamination when it reaches the interlaminar bonding area between two adjacent CLT layers as shown in Fig. 1c.

Fig. 2 shows a typical rolling shear failure found in the central layer of a CLT plate subject to out-of-plane loads. Interlaminar cracks between CLT layers are also shown here. 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 (Zhou, 2013), and therefore, its full understanding is of paramount importance to provide the required structural strength and prevent damage in CLT structures.

The fracture of quasibrittle materials like wood is characterised by a large Fracture Process Zone (FPZ) which develops ahead of the crack tip and where damage mechanisms such as microcraking and crack bridging take place. The Cohesive Zone Model (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; Barenblatt, 1962; Bazănt, 2002; Dugdale, 1960). However, the CZM must be implemented all along the potential crack paths and it needs a refined discretisation in order to describe the FPZ properly. Hence, when it is necessary to allow multiple crack fronts or to describe not well-known crack paths or crack positions (e.g. the simulation of rolling shear failure in CLT structures), the huge size of the resulting problem leads to consider the use of parallel computations based on domain decomposition methods (Farhat and Roux, 1991; Mandel, 1993). These are mature techniques for linear problems, but just recently have been developed to treat non-linearities (Guidault et al., 2008; Hinojosa et al., 2014; Saavedra et al., 2012).

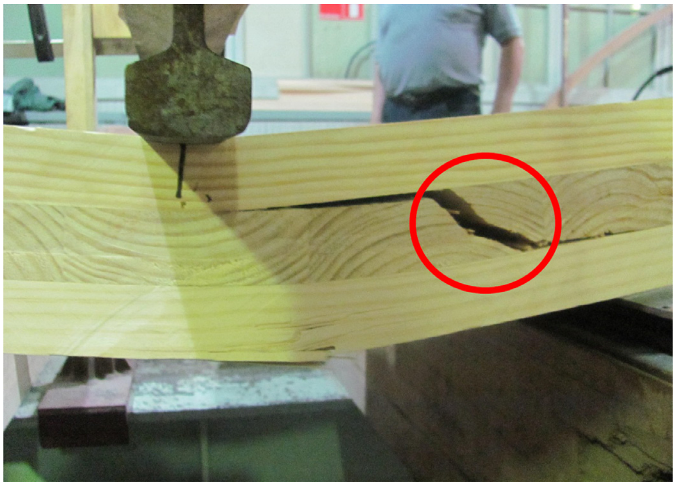

Fig. 2. Typical rolling shear failure (highlighted in the red circle) in the central layer of a CLT plate subject to three-point-bending. Interlaminar cracks are next to the red circle. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

In an attempt to shed more light on the simulation of rolling shear failure, we propose in this paper a modelling strategy which combines two approaches. Firstly, we make use of a homogenisation-based multi-scale modelling framework to determine the undamaged mechanical properties of wood. Secondly, we enrich this modelling procedure by using cohesive interfaces at the homogenised macroscopic structural scale in order to capture inter-fibre and interlaminar cracking in a CLT plate. In addition, a domain decomposition approach is used to solve the macroscopic equilibrium problem using parallel computations. Following this double modelling approach, along with the parallel solver, we are able to study the influence of wood density, edge-gluing and the span-to-depth ratio on the rolling shear failure in CLT.

This paper is organised as follows. Section 2 describes briefly the mathematical foundations of the multi-scale constitutive theory. The approach adopted to capture damage due to rolling shear and the parallel solver used to compute the response of the CLT structure are detailed in Section 3. Section 4 presents the multi-scale finite element simulation of CLT structures. The experimental work is described in Section 5. Some numerical predictions obtained by the present model are given in Section 6. Finally, Section 7 summarises our main conclusions.