Computers and Structures 177 (2016) 83–90

Contents lists available at ScienceDirect

Computers and Structures

journal homepage: www.elsevier.com/locate/compstruc

Multi-scale model updating for the mechanical properties of cross-laminated timber

E.I. Saavedra Flores [a,*], R.M. Ajaj [b], I. Dayyani [c], Y. Chandra [d], R. Das [e]

[a] Departamento de Ingeniería en Obras Civiles, Universidad de Santiago de Chile, Av. Ecuador 3659, Estación Central, Santiago, Chile
[b] Aeronautics and Astronautics, University of Southampton, Southampton SO171BJ, UK
[c] Centre for Structures, Assembly and Intelligent Automation, School of Aerospace, Transport and Manufacturing, Cranfield University, Cranfield MK43 0AL, UK
[d] College of Engineering, Swansea University, Singleton Park, Swansea SA2 8PP, UK
[e] Sir Lawrence Wackett Aerospace Research Centre, School of Engineering, RMIT University, GPO Box 2476, Melbourne, VIC 3001, Australia

ARTICLE INFO

Article history:
Received 28 July 2015
Accepted 31 August 2016

Keywords:
Cross-laminated timber
Multi-scale modelling
Finite elements
Genetic Algorithm

ABSTRACT

In this paper we propose a homogenisation-based four-scale model for the mechanical properties of cross-laminated timber. The spatial scales considered in this study are the wood cell-wall, the wood fibres, growth rings and the structural scale. The computational homogenisation scheme is solved sequently from the lowest to the highest level in order to determine the effective mechanical properties of each material scale. As we are interested in improving the predictions of our computational simulations, we propose an optimisation strategy to calibrate the micro-mechanical parameters. Our numerical predictions are compared with experimental results and are validated successfully.

1. Introduction

Over the last two decades or so, cross-laminated timber (CLT) has been gaining popularity in residential applications, mainly in Europe and North America. CLT is a relatively new building system based on structural panels made of several layers of boards stacked crosswise and glued together on their faces (Fig. 1).

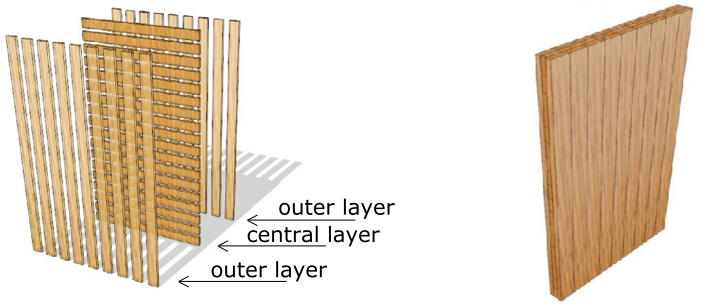
As CLT panels are light-weight structural elements with high stiffness and strength to bending, compression and shear, they are an economically competitive building system when compared to traditional options and therefore, are a suitable candidate for some applications which currently use concrete, masonry and steel [2]. CLT has multiple advantages including its favourable seismic performance, its ability to self-protect against fire, its lessened environmental impact and its renewable material source [3].

In spite of the advantages of building with CLT, and the considerable growth that the total production is experiencing in the world market [4], the benefits of using CLT and in general timber, in the construction industry are still far from maximised. This is mainly due to the fact that dimensioning practices and many existing structural design rules are still based on an empirical background [5]. Different methods have been adopted for the determination of the basic mechanical properties of CLT. However, to date no method has been universally accepted by CLT manufacturers and designers [6].

The reason for the slow progress in the development of timber design codes, and in particular, in the difficulties to fully understand the mechanics of timber materials, lies mainly in the highly complex and intricate nature of wood microstructure [7]. At very small scales, wood shows a complicated hierarchical nature distributed across multiple spatial scales, from submicrometer dimensions to macroscopic scales. This important feature has been a subject of intensive research over the last few years by means of multi-scale homogenisation techniques. Initial investigations were carried out by Holmberg et al. [8] on the mechanical behaviour of wood from a micro up to a macro level. They obtained numerically stiffness and shrinkage properties and compared them with experimental data. Hofstetter et al. [9] suggested five elementary phases for the mechanical characterisation of wood. These were hemicellulose, lignin, cellulose, with its crystalline and amorphous portions, and water. Qing and Mishnaevsky [10] studied the effect of wood density, microfibril angle (MFA) and cell shape on the longitudinal tensile strength of softwood. Rafsanjani et al. [11,12] investigated experimentally and numerically the hygroscopic swelling and shrinkage properties of softwood. Saavedra Flores and Friswell [13] investigated the deformation and failure mechanisms of wood at the ultrastructural scale. They also studied the development of a new material inspired by the mechanics and structure of wood cell-walls [14]. In the context of multi-scale modelling of CLT

* Corresponding author.
E-mail address: erick.saavedra@usach.cl (E.I. Saavedra Flores).

http://dx.doi.org/10.1016/j.compstruc.2016.08.009
0045-7949/



(a) The layers of boards are stacked crosswise

(b) The three layers of boards are glued on their faces (final configuration)

Fig. 1. Schematic representation of a typical CLT panel [1].

structures, Saavedra Flores et al. [15,7] investigated the structural behaviour of CLT by linking three different scales. We note, however, that despite the increasing interest in this subject, the complete understanding of the mechanical properties of wood, and in particular cross-laminated timber, 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 [15,7] by introducing the following new features:

1. The explicit modelling of growth rings as a new material scale.
2. Multi-scale model updating by means of a Genetic Algorithm (GA).
3. Investigation of the influence of wood density on the mechanical properties of CLT.
4. New experimental results.

This paper is organised as follows. Section 2 describes briefly the mathematical foundations of the multi-scale constitutive theory. Section 3 presents the strategy adopted for the multi-scale modelling of timber structures. The experimental works are described in detail in Section 4. Section 5 introduces the use of the GA technique to improve our numerical predictions. The validation of our (updated) model along with some numerical predictions are presented in Section 6. Finally, Section 7 summarises our main conclusions.

2. Multi-scale constitutive theory

Multi-scale models enable specifying the relationships between physical variables observed at different length scales. These are of particular importance in the study of heterogeneous materials with hierarchical microstructures in which the macroscopic response of the material can be predicted from the information coming from the microscopic (or lower) level.

In the present type of homogenisation-based multi-scale constitutive theory, 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 also assumed that the macroscopic or homogenised strain tensor component ε_{ij} at any arbitrary point of the macroscopic continuum is the volume average of the microscopic strain tensor component $\varepsilon_{\mu_{ij}}$ over the domain Ω_μ of the RVE. Similarly, the macroscopic or homogenised stress tensor component σ_{ij} is assumed to be the volume average of the microscopic stress tensor component $\sigma_{\mu_{ij}}$ over Ω_μ.

In addition, we can introduce a convenient decomposition in the total displacements field over the RVE domain as a sum of a linear displacement component and a displacement fluctuation $\tilde{u}_{\mu_i}$ which represents local variations about the linear displacement component and does not contribute to the macroscopic scale strain.

By taking into account the Hill-Mandel Principle of Macro-homogeneity [16,17], which establishes that the macroscopic stress power must equal the volume average of the microscopic stress power over Ω_μ, the virtual work equation for the RVE can be reduced to

$$\int_{\Omega_\mu} \sigma_{\mu_{ij}} \delta\varepsilon_{ij}\, dV = \int_{\Omega_\mu} \sigma_{\mu_{ij}} (\partial\eta_i/\partial y_j + \partial\eta_j/\partial y_i)/2\, dV = 0, \tag{1}$$

with $\delta\varepsilon_{ij}$ representing the Cartesian components of the kinematically admissible virtual strains field, η_i a component of the virtual displacements vector, both at the RVE level, and y_i a local (RVE) coordinate. We note in Eq. (1) that, the Hill-Mandel Principle requires the RVE body force and external surface traction fields to produce no virtual work [18].

As it stands, Eq. (1) leads to an ill-posed microscopic equilibrium problem. Therefore, in order to make problem (1) well-posed, we introduce in the present multi-scale constitutive framework a set of kinematical constraints on the displacement fluctuations (belonging to the vector space of virtual displacements) to be imposed in the RVE. The choice of different kinematical constraints defines different classes of multi-scale constitutive models. Probably the most popular classes are the Taylor model, or *rule of mixtures*, and the Periodic boundary displacement fluctuations model.

The Taylor model is obtained by setting to zero all the displacement fluctuations in the RVE domain. This choice implies that the corresponding total microscopic displacement field varies linearly in Ω_μ and that the microscopic strain field is homogeneous. One important drawback of the Taylor kinematical constraint is the fact that it does not consider the mechanical interaction among the different solid phases or between the solid phases and micro-voids. For this particular class of model, the homogenised constitutive tangent operator is calculated by

$$D^{hom}_{ijkl} = D^{taylor}_{ijkl} = \frac{1}{V_\mu} \int_{\Omega_\mu} D_{\mu_{ijkl}}\, dV, \tag{2}$$