23rd Australasian Conference on the Mechanics of Structures and Materials

2014

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Publication details

Lewis, K, Shrestha, R & Crews, KI 2014, 'Introduction to cross laminated timber and development of design procedures for Australia and New Zealand', in ST Smith (ed.), *23rd Australasian Conference on the Mechanics of Structures and Materials (ACMSM23)*, vol. I, Byron Bay, NSW, 9-12 December, Southern Cross University, Lismore, NSW, pp. 601-606. ISBN: 9780994152008.

INTRODUCTION TO CROSS LAMINATED TIMBER AND DEVELOPMENT OF DESIGN PROCEDURES FOR AUSTRALIA AND NEW ZEALAND

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ABSTRACT

Cross-laminated timber (CLT) is an engineered wood product which is gaining popularity in Europe and North America as a sustainable alternative to concrete and steel construction in commercial and multi-residential buildings. CLT is a panel type product made up of 3 or more layers of timber boards each layer running in orthogonal directions and can be used as wall or floor panels.

Investment in sustainable softwood plantations over the past few decades has meant that there is now an abundant supply of renewable timber resources ready to be utilized, to produce light weight buildings with low carbon footprints, smaller foundations and transport requirements and increased speed and ease of construction.

There is an increasing interest within the construction industry in Australia to start producing CLT panels. Research at the University of Technology Sydney has shown that CLT panels manufactured within Australia from Australian grown timber can compete with international products. CLT floor panels have been found to have significant strength to weight benefits, the potential to be used as two-way spans, higher than predicted char ratios and can comply with Building Code of Australia (BCA) requirements for acoustic design.

This paper presents an overview of research and work completed to date, and a discussion of issues that have been identified and addressed to establish design procedures for CLT to meet Australian building standards and code requirements.

KEYWORDS

Timber, EWP, CLT, design procedures,

INTRODUCTION

Cross-laminated timber (CLT) is an engineered wood product (EWP) generally manufactured from low grade raw materials. EWPs are produced by binding or fixing a raw timber material together, typically using an adhesive, to form a composite wood product. The base materials are boards of timber which are laid side by side to form a plate layer. A CLT panel is usually composed of an uneven number of layers, generally 3 or 5 but sometimes more. Each layer is laid 90 degrees to the adjacent layer forming a solid wood panel and improving the structural properties of the raw material.

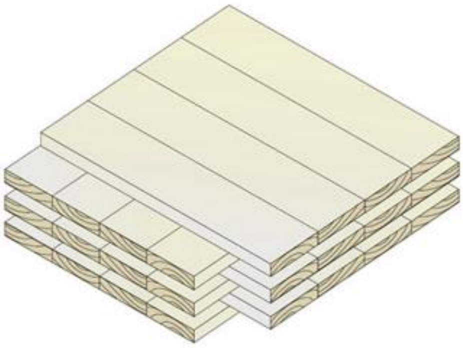

Figure 1. CLT construction (FPInnovations, 2010)

CLT can be used for wall panels, floor panels, roof panels, curved roof panels and beams. Elements work as load bearers and often provide lateral stability in conjunction. The panels are prefabricated and have dimensions that allow large wall and floor panels, with openings freely placed.

History and Benefits

CLT was first developed in Austria and Germany in the 1990's and has been gaining increasing popularity. There are now several established manufactures of CLT in Europe, a few in North America and one in New Zealand. The increase in the design and construction of CLT structures is largely driven by the green building movement, changing public perceptions towards the benefits of timber construction and extensive research that has resulted in product approvals (Thiel, 2014).

Current European research is aimed at producing harmonized design procedures and the establishment of a design standard for CLT. Apart from a draft European product standard for CLT, prEN 16351, which provides the performance requirements for the production of CLT, there is not yet a European design standard. A software tool, CLTdesigner has been developed at Graz University Austria that encompasses the latest design procedures.

Inspired by the success of CLT in Europe, Canada began a research group in 2005 within FPInnovations, a non-profit timber research centre. This resulted in the release of a comprehensive CLT Handbook in 2010 that provides in depth details of manufacturing, design and serviceability (FPInnovations, 2010). Following this, a North American CLT product standard, Standard for Performance Rated CLT was published in 2011.

Worldwide sales of CLT have reached a figure of approximately 500,000 m^3 (Brandner, 2014). Within Europe, modern one-family houses are popular due to the excellent thermal properties of CLT; however it has also become popular in multi-storey building construction. There are now several examples of CLT buildings up to 10 stories around the world.

CLT has shown competitiveness with steel and concrete, its edge over these traditional construction materials comes from its fast build program allowing an earlier income of rents and reduced financing costs, (Zumbrunnen, 2012). The decreased build time has secondary benefits such as reduced disruption to neighbours. Since CLT is prefabricated in a factory, weather delays are not an issue during manufacturing. Openings are cut out during fabrication which means doors and windows can be ready to install immediately without onsite measurements. Other benefits that contribute to the decreased build time are that timber is flexible and less labour intensive to install fixings and services.

CLT has a favourable strength to weight ratio which has benefits for sites constrained by poor soil. A CLT building allows multi-storey buildings to be constructed on sites that have weight limits due to poor soil or underground services.

Wood is approximately 50% carbon, making a CLT building a carbon sink. Decreased build times, transportation and craning requirements result in decreased greenhouse gas emissions during construction. At the decommissioning of a CLT building, the panels can be dismantled in the same way they were installed. Every layer of CLT can be removed and reused. If there is no possibility of reuse then the panels can be converted to EWPs or be recycled as biomass fuel (Zumbrunnen, 2012).

CLT in Australia

The construction cost of single storey dwelling houses in Australia has been kept low due to competitiveness and cheap building materials; commonly masonry and timber. However multi-storey buildings have a significantly higher cost, primarily due to the high cost of steel and concrete and labour costs (Zumbrunnen, 2012). CLT offers a competitive product within this market due to the low cost of timber, its fast build time and the shift towards sustainable construction technology.

There is limited manufacturing capacity within New Zealand and in Australia it is non-existent. The market in New Zealand is driven by the beneficial earthquake design properties achieved with timber buildings and research by the Structural Timber Innovation Company, STIC, a collaboration between industry and research organisations in New Zealand and Australia formed in 2009 (Crews, 2011).

The Forte building in Melbourne is a 10 storey CLT residential block built in 2012 that demonstrates CLTs suitability for use in Australia. However since Australia currently has no manufacturing capabilities all material was supplied by KLH, an Austrian CLT plant. For CLT to become a competitive construction material, local resources and processes need to be utilised.

CLT panels are generally fabricated with soft wood. In Europe commonly spruce is used. Within Australia it is proposed to construct panels using locally grown pine. Experimental research at the University of Technology Sydney (UTS) has shown that Australian sourced pine has properties comparable with European spruce and could be used to successfully manufacture CLT panels.

DESIGN METHOD

To establish a design procedure for CLT within Australia and New Zealand it is proposed to modify the following European design procedure to meet Australian standards. Figure 2 summarises the current design procedures available.

Manufacturing

CLT panels are used as wall, floor, roof and beam elements, made from a variety of softwood and sometimes hardwood species, have different cross section dimensions and layout of boards, and can be manufactured with various methods. Because of these parameters, various design models exist.

To ensure consistency and to meet standards, European manufacturers are provided with guidelines for dimensions and quality requirements from the draft product standard, prEN 16351. Material is to be visually or mechanically graded according to EN 14081-1 or DIN 4074-1 and within a single layer all boards have to be of the same grade; otherwise the grade of the single layer has to be assigned according to the lowest grade element. In Europe strength grades according to EN 338 apply.

Determine Loading

Whether the design is for a floor or wall element, each panel usually experiences in-plane loads and out-of-plane loads simultaneously. A floor element will experience both bending action from vertical loads and shear action from horizontal loads whereas a wall element will experience 3 major loads, bending from wind, axial from vertical loads and shear from horizontal loads. It is recommended to avoid any load situation where tension is applied perpendicular to the timber grain. Both the adhesive and the timber show poor resistance in this load situation (Thiel, 2014).

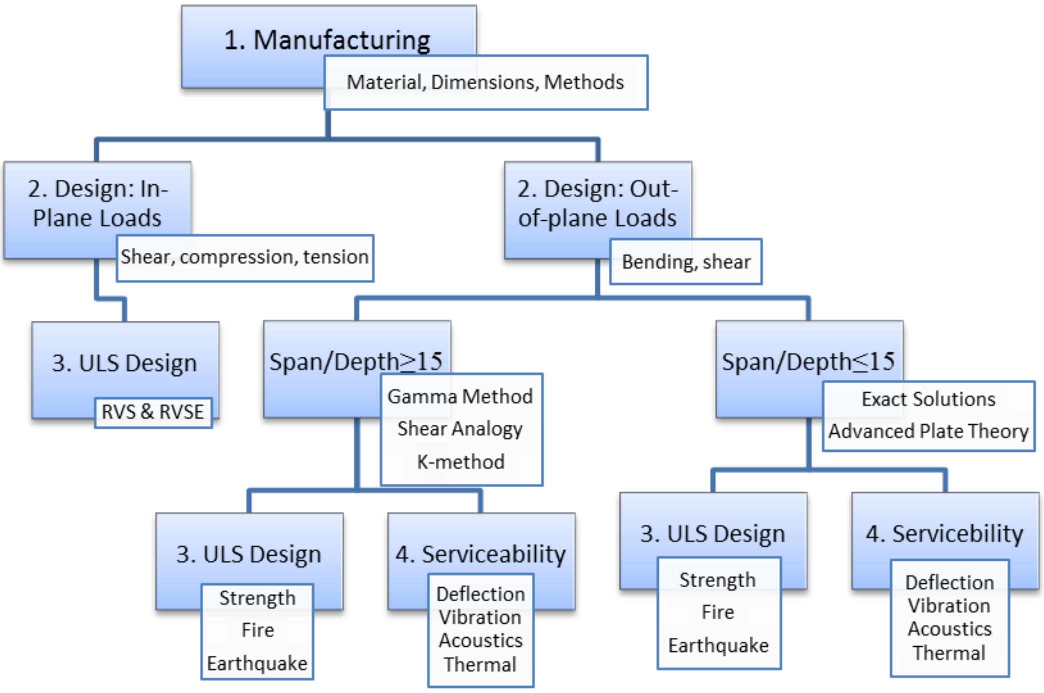

Figure 2. Flow chart of CLT design process.

Out-of-plane loading

There are numerous procedures for the design of CLT in bending out-of-plane. These have been developed based on the fact that CLT cannot be viewed as a homogenous material. In particular the shear flexibility due to the transverse layers has to be considered. This shear stress causes a reduction in the bending capacity, an inter-plane slip, known as the rolling shear.

For out-of-plane loads, the gamma method is commonly used which is outlined in Eurocode 5, Annex B. Also considered is the slightly more complex shear analogy method that directly accounts for shear deformation (FPInnovations, 2010). These methods were originally used for the analysis of composite beams with mechanical fasteners and have been modified for CLT. The transverse layers of CLT are assumed to be fasteners between the primary layers and represent the rolling shear slip.

The k-method is an alternative method that is based on Timoshenko's beam theory and is used in calculations for plywood. It calculates a composition ratio to predict the expected properties of the panel which accounts for the bending capacity reduction due to the transverse layers. All three methods are approximations based on beam theories. From practice it is known that CLT design is commonly governed by deflections and vibrations and that within the range of length/thickness ≥ 15 all three methods compare well and are therefore all applicable (Thiel, 2014). Tests were conducted at UTS in accordance with AS4063 that indicated the gamma method was the most accurate with the other methods slightly underestimating the stiffness properties.

These theories are limited as the analytical models are based on beam theory, whereas CLT is a plate element. For large point loads, to account for two-way spanning effects and for length / thickness ≤ 15 a more advanced examination is recommended. Advanced laminated plate theories requiring higher computational input have been developed and recommended in these cases (Thiel, 2014).

In-plane loading

At the Graz University, the representative volume element, RVE, is proposed to calculate in-plane loads (Bogensperger, 2010). The size of one RVE is dictated by the thickness of the CLT panel and the width of a single board plus half of the gap width on each side. The RVE is subjected to only in plane stresses (normal and shear) and therefore the stresses and strains are constant over the entire cross section. If the thickness is equal for all layers the RVE can be further divided into a representative volume sub-element, RVSE (see Figure 3). An RVSE has the same square surface but with a thickness composed of half the board thickness on both sides of an adhesive layer acting as a plane of symmetry.

In manufacturing it is common not to edge glue (narrow face) all CLT boards. Further, even with edge gluing cracks can form due to swelling and shrinkage. This means that shear forces will be acting in different directions on adjacent planes and cause a torsional stress at the glued interface. Therefore the RVSE is used to calculate both shear and torsional stresses. This method is only valid for constant layer thickness, therefore for layouts with various thicknesses and strength grades it is recommended to adopt load bearing and design models that are available for glued laminated timber.

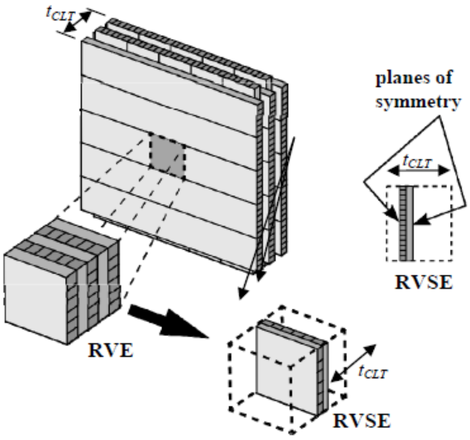

Figure 3. Definition of RVE and RVSE on a CLT element (Bogensperger, 2010).

Ultimate Limit State

Bending, tension, shear and compression ultimate limit state (ULS) design capacities are calculated according to the theory discussed in the previous section. Further considerations for ultimate limit state design needs to take into account fire design and earthquake design.

To check the strength capacity of the CLT during a fire, design is based on the reduced cross sections according to EN 1995-1-2. The charring depth depends on the adhesive applied, the gap size between boards and the availability of fire protection. The charring rate for softwoods and beech with density greater than 290 kg/m3 is $\beta = 0.65$ mm/min for gaps up to 2 mm and $\beta = 0.80$ mm/min for gaps up to 6 mm. If the adhesive is not temperature proofed it has been observed that the charred layers of CLT elements loaded out of plane can detach.

Fire tests at UTS were conducted on CLT panels composed of various pine species in accordance with AS/NZS 3837:1998. The charring rate of pine with no gaps calculated from AS1720.4-2006 is 0.75 mm/min for Hoop and Radiata and 0.64 mm/min for Slash pine. The experimental results on CLT panels with gaps displayed larger charring rates, close to the value of $\beta = 0.80$ mm/min provided by EN1995-1-2.

Timber structures are lightweight and therefore the seismic actions are lower. However the key to seismic design is structural ductility as it allows energy dissipation. Compared to the steel connections used to connect CLT panels, the panels themselves have infinite stiffness. The ductility of the structure therefore needs to be designed into the connections to ensure good seismic behaviour. Capacity based design is proposed for seismic design as it aims to prevent brittle failure. By oversizing the CLT panels there is a global ductile failure mechanism at the connections (Fragiacomo, 2014). Formulas provided by Eurocode 5 for connections with metal fasteners are used to ensure the connections are dissipative. In a CLT building these connections are the vertical screwed connections between wall panels, connections of wall to floor using angle brackets to resist shear and hold down connections at each end of a wall element to resist uplift.

Serviceable Limit State

It is critical to calculate the deflection of CLT elements out-of-plane. Due to the cross-layers in CLT, the rolling shear has to be taken into account as well as the bending. The analytical models discussed in 2.1 are used to calculate the modulus of elasticity and the shear moduli to determine the deflection. Long term deflections taking into account creep must also be factored in. The factors for creep have been given by prEN 16351 and are dependent on the amount of moisture and relative humidity the structure is exposed to. There is currently little information on how these values compare with CLT panels composed of Australian and New Zealand pine species.

For CLT elements with spans larger than 4m, the critical design parameter is commonly vibration (Thiel, 2014). CLTdesigner follows the procedure detailed in EN 1995-1-1 that checks the natural frequency, stiffness criteria and vibration acceleration. Floor panel dynamics are complex within a structure due to the panel's sensitivity to boundary conditions. Tests conducted at UTS were inconclusive and a more comprehensive analysis is required.

CONCLUSIONS

CLT has been used extensively throughout Europe with continued success. A design method for CLT has been outlined according to European standards and methods. It is proposed to modify these design guidelines to meet Australian standards and be applicable to local species of timber. Experiments on CLT panels constructed with various pine species from Australian forests have indicated that softwood pine sourced locally compared well to analytical models and European research and hence has manufacturing potential.

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