FEASIBILITY STUDY OF NEW ZEALAND RADIATA PINE CROSS-LAMINATED TIMBER

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ABSTRACT

Cross-laminated timber (CLT) as a structural system is used in increasing volumes in Europe, however this is not the case in New Zealand despite the large volume of timber available and CLT panels representing a lighter and greener alternative to precast concrete for walls and floors. This study aimed to establish the use of CLT in New Zealand using locally grown Radiata pine, laid crosswise into panels either three or five layers thick, 1000 mm wide x 4000 mm long and bonded using resorcinol adhesive. Panels were subjected to bending and stiffness testing out of plane to establish yield strength and modulus of elasticity. CLT panels were generally, but not always, stronger than their constituent boards with bending strengths ranging from 28 to 51 MPa. MOE results from this study ranged from 7.6 to 12 MPa. Bending strengths were predicted with various models, most accurately using those accounting for rolling shear.

INTRODUCTION

Cross-laminated timber is a structural timber product gaining popularity in Europe, but it is not yet available in New Zealand.

New Zealand produces a large volume of timber per year of which Radiata pine is the primary plantation species in New Zealand; around 90 % of production forests are Radiata pine. The popularity of the species is largely due to its short harvest time (25-30 years), and high timber yields. Good sites can achieve high quality timber at 30 m^3/ha/year, or up to 50 m^3/ha/year [11]. Despite the large volume of timber available it is mainly exported in its raw form so CLT is a product which may offer significant added value.

Wood in its natural state is a very strong material with a higher strength to weight ratio than steel, concrete, and masonry [6]. Timber is also a natural, renewable resource [6]. A number of countries have introduced measures requiring buildings to use a percentage of renewable resources [21] so replacing construction elements, such as walls and floors, often formed in concrete, with timber, is one method of achieving this goal.

Cross laminated timber (CLT) is a panel product manufactured by gluing layers of parallel boards, planks or laths [2]. Layers of boards are laid orthogonally [7, 9, 12]. CLT has an odd number of laminates (typically 3, 5 or 7), so that face layers are parallel [9, 12, 19].

Laminated timber removes the natural variations in timber strength, such as knots. By cross-laminating the boards, there is a reduction in the differential between the strength perpendicular to the grain and parallel to the grain [10, 16].

Lamination of the panels used resorcinol formaldehyde resin adhesive. This was chosen because it was readily available, proven in other CLT research [13, 14], cost effective and is commonly used in glue-laminated timber production using Radiata pine in New Zealand (NZS 3606, Standards New Zealand, 1993).

CLT panels were subjected to four point bending tests to establish MOE and bending strength. Calculation methods were then used to predict bending strength, based on MOE results from acoustic testing.

METHODOLOGY

Fabrication of the CLT panels represented a significant portion of this study given that (to the best of our knowledge) this has not been undertaken in New Zealand previously.

The timber used for the panels was all New Zealand, plantation-grown, Radiata pine which was kiln dried before delivery. The 90 x 41 mm timber had been machine stress graded to MSG8 [17]. The timber had been gauged to size in the sawmill (as is common with framing timber). In order to provide a surface which was sufficiently smooth for laminating, the boards were then machined on their wide faces. This process also reduced the variance in board thickness, which further aided bonding by ensuring that the glue surface has more even. The timber was laminated within 72 hours of the timber being machined [8] to ensure that the moisture content at the surface of the timber was optimal for adhesion.

For this study the CLT panels were created using two thicknesses of laminates; 100 x 21 mm and 90 x 41 mm. A combination of five-layer and three-layer CLT was fabricated. These were selected as timber sizes commonly available in New Zealand and both the sizes and number of laminates are in line with those commonly produced in Europe [10].

Selection of the timber boards for laminating is fundamental to the philosophy of creating CLT; higher strength boards are used in the outer layers and lower strength boards are used internally. For this study the boards were selected based on moisture content (any over 16% were rejected, due to expected poor glue adhesion) and modulus of elasticity (MOE). Grading by MOE was conducted using a Hitman HM200, which measures the velocity of sound waves in the timber, then correlated to MOE using equation 1, as per the manufacturer's literature [5]:

$$E = \frac{velocity^2}{density} \qquad (1)$$

The boards were then ranked by MOE. For each timber size the boards were sorted into strongest (for the outer, longitudinal laminates), weakest (for inner longitudinal laminates – 5 layer only) and mid-strength (for lateral laminates). Boards were then cut to length.

Resorcinol formaldehyde resin was chosen as the adhesive for the panels based on its ease of application, ability to cure at room temperature and widespread use in the timber industry. The adhesive was supplied by Hexion Adhesives, as a two part adhesive (Silvic R15 resin and Silvic RP50/RP51 hardener). These were mixed in the prescribed 3:1 ratio (by weight) just prior to use, measured into jugs with the correct quantity to provide one layer at 250 g/m^2. Adhesive was applied evenly across the surface using rollers, left for 10 minutes and then the panels were assembled into the press.

Multiple layout areas were used to allow three panels to be fabricated in each pressing, without exceeding the 45 minute working time of the adhesive. Curing of the panels occurred within a press formed on the strong floor of the laboratory. Pressure was applied via threaded rods at 400 mm centres both sides of the panel, through 105 mm thick LVL crossbeams sitting above a full length 105 mm thick LVL panel. The threaded rods were hydraulically tensioned to achieve a pressure of 0.7 MPa within the press [8]. This load was applied within 15 minutes of the completion of the gluing. Configuration of the press, with three panels during curing is shown in Figure 1.

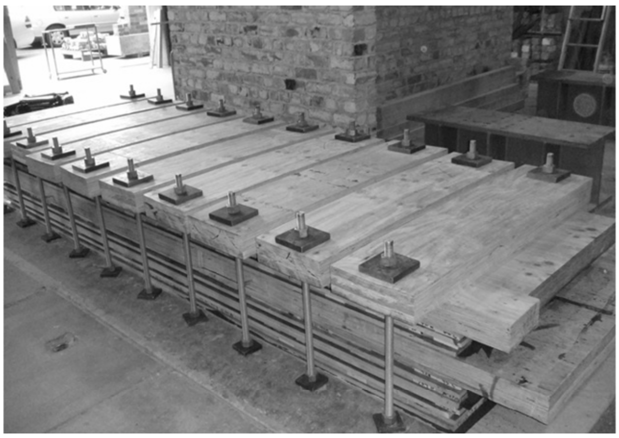

Figure 1. Press with three CLT panels curing

CLT panels were subjected to four-point bending tests to failure. This was undertaken in line with the parameters given for stiffness testing, as part of machine stress grading AS/NZS 4063 [15] which specifies four point testing, as well as the minimum span and configuration of load points, as shown in Figure 2.

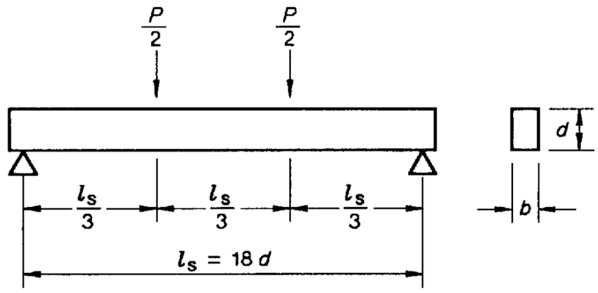

Figure 2. Testing configuration for bending and MOE testing (AS/NZS 4063) [15]

Using this technique the bending strength of the panels was calculated, based on failure loads. Deflection logging will also allow calculation of the MOE for the panel as a whole.

A selection of individual boards (those graded, but not used in fabrication) were also tested for bending strength and MOE (using a four point bending configuration).

All bending tests were undertaken using a 500 kN capacity MTS testing machine. Load data, as well as deflections at midspan and above the supports (to measure support compression) were recorded continuously throughout the testing.

RESULTS

During the fabrication process the boards were pushed firmly against the neighbouring boards by hand, but without clamping forces in the horizontal direction. This allowed the natural bow evident in particularly the 4 m lengths to form a gap to the neighbouring board. The significance of these gaps was expected to be minimal, given that the boards were not expected to transfer load to the neighbouring boards through direct contact. However, there may well be some reduction in strength owing to the decrease in timber per unit width of the face due to the gaps. Aesthetically this is likely to be more of a concern, as the gaps detract from the finish of the panels, as can been seen in Figure 3.

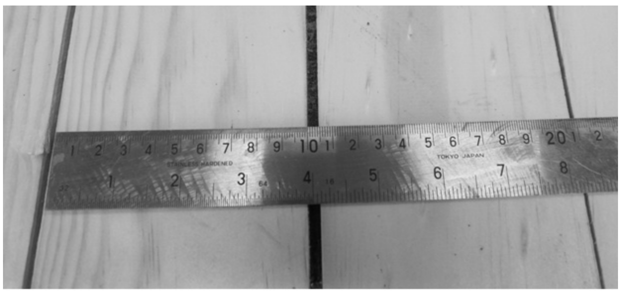

Figure 3. Gaps between outer boards after fabrication

The gaps also resulted in the edges of the panels being ragged, in spite of the timber being accurately cut to length beforehand. This was trimmed off to provide well-finished products, which is the most likely finish in commercial fabrication.

In this research the 90 x 41 mm boards were machine stress graded to AS/NZS 1748 [17] prior to supply and so the strength of the boards was greater and less variable. The timber supplied was certified as MSG8. The 100 x 21 mm boards were supplied ungraded resulting in a greater variation and included more weaker boards, as shown in Table 1.

Table 1. MOE of individual boards

Boards	Mean (GPa)	Standard Deviation
90 x 41 mm	9.60	1.56
100 x 21 mm	10.6	2.94

The standard deviation of the MOE was roughly twice for the ungraded boards compared with the graded boards, which means that the CLT panels fabricated from ungraded boards will have a greater variation in strength between the inner laminates and outer laminates. This variance can be seen in the difference between the MOE values shown in Figure 4 and Figure 5.

The ungraded panels showed higher peak values as the graded boards are selected to have their MOE within a given range. Resulting in CLT slabs with less variation between the inner and outer layers, therefore minimising one of the benefits of CLT fabrication.

CLT panels all demonstrated brittle mode failures, as expected with timber. Some of the panels experienced obvious rolling shear failures, with longitudinal cracks forming within the cross-wise laminate under tension. These were coupled with tensile failures in the outer laminates. Other panels demonstrated tensile failures in the outer laminates which then propagated through the cross-wise layer between the panels, causing failure of the upper layers in bending.

ANALYSIS

Bending strength and moment capacity of the CLT panels was predicted from the MOE values of the boards obtained by acoustic testing. These values were correlated to bending strength of the boards using methods by Walford [20] and then used to predict the moment capacity for the section.

Multiple models were utilised in this study to assist with the prediction of the moment capacity for the CLT panels. Simple models were initially tested, with the panel assumed to be one solid isotropic cross-section, similar to sawn timber sections. This method grossly

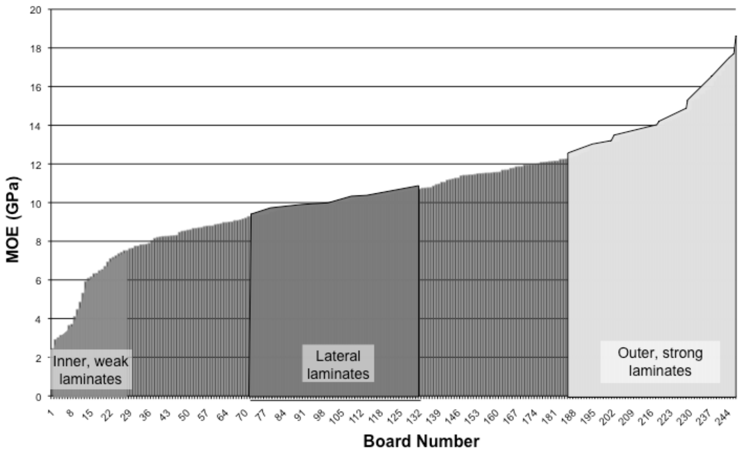

Figure 4. Selection of boards for 100 x 21 mm panels

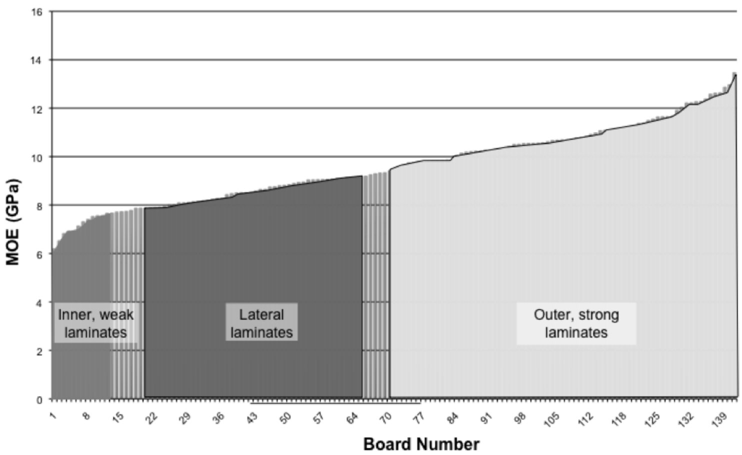

Figure 5. Selection of boards for 90 x 41 mm panels

over-predicted the moment capacity of the section because it ignored the reduced capacity of the layers loaded perpendicular to the grain. Transformed section models [1], I-joist models [4] and plywood models [18] were more accurate than prior models. However, a final model using the methods by Blass and Fellmoser [3], given in equations 2-4, combined with the bending strength prediction correlation from Walford [20], given in Table 2, was most successful.

Configuration factors for loadings parallel and perpendicular to the plane of the panel and to the grain was proposed by Blass and Fellmoser [3] allowing for a reduction in bending strength of the laminates. The bending tests on the CLT panels in this study were loaded perpendicular to the plane of the panel and bent parallel to the grain of the face laminates. For this configuration the composition factor, K_1 is given by equation 2:

$$k_1 = 1 - \left(1 - \frac{E_{90}}{E_0}\right) \frac{a_{m-2}^3 - a_{m-4}^3 + ... \pm a_1^3}{a_m^3} \tag{2}$$

Where m is the number of layers in panel
a_m is the thickness of m layers in mm
E_0 is the MOE parallel to the grain in MPa (by sonic testing)
E_{90} is the MOE at 90° to the grain in MPa

For this calculation E_{90} was taken as being $E_0/20$, given by Buchanan [4]. In this method the ratio of E_0/E_{90} is suggested as being 30. It was considered that the figure of 20 was most appropriate for Radiata pine, whereas the 30 relates to research undertaken on spruce.

Bending strength of the panels was then calculated using equation 3.

$$f_{b,0,eff} = f_{b,0} k_1 \tag{3}$$

where $f_{b,0,eff}$ is the effective bending strength of the timber parallel to grain in MPa
$f_{b,0}$ is the bending strength of the timber parallel to the grain in MPa, correlated from the sonic testing results.

The moment capacity of the section can then be calculated as previous, using equation 4.

$$M = f_{b,0,eff} Z_{eff} \tag{4}$$

Bending strength of the boards was predicted using the correlation by Walford [20], given in equation 5.

$$f_b = 5.0583\ E - 9.8669 \tag{5}$$

This gave the bending strength results shown in Table 2. This gave mean bending strengths for the 100 x 21 mm five layer panels of 48.1 MPa, for the 90 x 41 mm three layer panels of 36.1 MPa and for the 90 x 41 mm five layer panels of 27.6 MPa. The mean MOE for these panels was 11.3 GPa for the 100 x 21 mm five layer panels, 10.1 GPa for the 90 x 41 mm three layer panels and 7.63 GPa for the 90 x 41 mm five layer panel.

Table 2. MOE from sonic testing data correlated to bending strength using Walford's correlation [20]

Board dimension	Board Grade	MOE by sonic testing (GPa)	F_b by correlation (MPa)
100 x 21	Strong	14.4	63.0
100 x 21	Medium	10.0	40.7
100 x 21	Weak	5.58	18.4
90 x 41	Strong	10.9	45.3
90 x 41	Medium	8.50	33.1
90 x 41	Weak	7.06	25.8

DISCUSSION

New Zealand grown Radiata pine was used successfully to fabricate CLT in this study. Boards were oriented longitudinally on the outer layers and cross-wise at alternate layers. Panels were created with three and five layers, using 100 x 21 mm and 90 x 41 mm boards. Locally sourced resorcinol formaldehyde resin adhesive (SYLVIC R15 resin, L5 hardener) was used to bond the panels, spread at 250 g/m^2 and performed well.

The CLT panels in this study were tested to destruction using a four-point bending configuration so as to achieve pure bending in the central third span. Failures of all six panels occurred on the tension face, as is typical for timber and large planes of rolling shear failure were observed.

Multiple models were utilised in this study to assist with the prediction of the moment capacity for the CLT panels. Simple models were initially tested, with the panel assumed to be one solid isotropic cross-section, similar to sawn timber sections. This method grossly over-predicted the moment capacity of the section because it ignored the reduced capacity of the layers loaded perpendicular to the grain. Transformed section models [1], I-joist models [4] and plywood models [18] were more accurate than prior models. However, a final model using the methods by Blass and Fellmoser [3] combined with the bending strength prediction correlation from Walford [20] was most successful. This gave mean bending strengths for the 100 x 21 mm five layer panels of 48.1 MPa, for the 90 x 41 mm three layer panels of 36.1 MPa and for the 90 x 41 mm five layer panels of 27.6 MPa. The mean MOE for these panels was 11.3 GPa for the 100 x 21 mm five layer panels, 10.1 GPa for the 90 x 41 mm three layer panels and 7.63 GPa for the 90 x 41 mm five layer panel.

These values of bending strength were found to be similar to those recorded by Vessby et al., [19] who found bending strengths between 39.5 MPa and 51.1 MPa for spruce CLT. This study also found values in excess of the 10 MPa allowable stress given by KLH for their spruce CLT, although the sample size was not large enough to be able to predict the characteristic strength for the panels.

CONCLUSION

This study demonstrates that it is possible to construct CLT using New Zealand grown Radiata pine.

Brittle mode failures were found, as is typical for timber. Failures typically occurred on the tension edge of the slab. Additionally there were planes of rolling shear within the cross-wise layers.

Prediction methodologies evaluated found that those which incorporated rolling shear were more accurate, particularly that by Blass & Fellmoser [3]. Correlation of MOE values obtained by sonic testing were correlated to bending strengths following methods by Walford [20].

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