Final Report
Project NT016

Developing laminated structural elements from fibre-managed plantation hardwood

2023

Launceston Centre
Funded by the Australian Government, Tasmanian Government & Industry Partners.
nifpi.org.au

NATIONAL INSTITUTE FOR
FOREST PRODUCTS INNOVATION
LAUNCESTON

Developing laminated structural elements from fibre-managed plantation hardwood

Prepared for

National Institute for Forest Products Innovation

Launceston

by

Dr Assaad Taoum, Prof Dr Christophe Sigrist and Prof Dr Martin Lehmann

Publication: Developing laminated structural elements from fibre-managed plantation hardwood

Project No: NIF080-1819 [NT016]

IMPORTANT NOTICE

ISBN: 978-1-922718-28-0

Researcher/s:
Dr Assaad Taoum, Prof Dr Christophe Sigrist and Prof Dr Martin Lehmann, University of Tasmania, T40B Newnham Campus, Newnham TASMANIA 7248

This work is supported by funding provided to Forest and Wood Products Australia (FWPA) to administer the **National Institute for Forest Products Innovation** program by the Australian Government Department of Agriculture, Fisheries and Forestry and the Tasmanian Government.

Australian Government
Department of Agriculture, Fisheries and Forestry

Tasmanian Government

Forest and Wood Products Australia
Level 11, 10-16 Queen St, Melbourne, Victoria, 3000
T +61 3 9927 3200 F +61 3 9927 3288
E info@nifpi.org.au
W www.nifpi.org.au

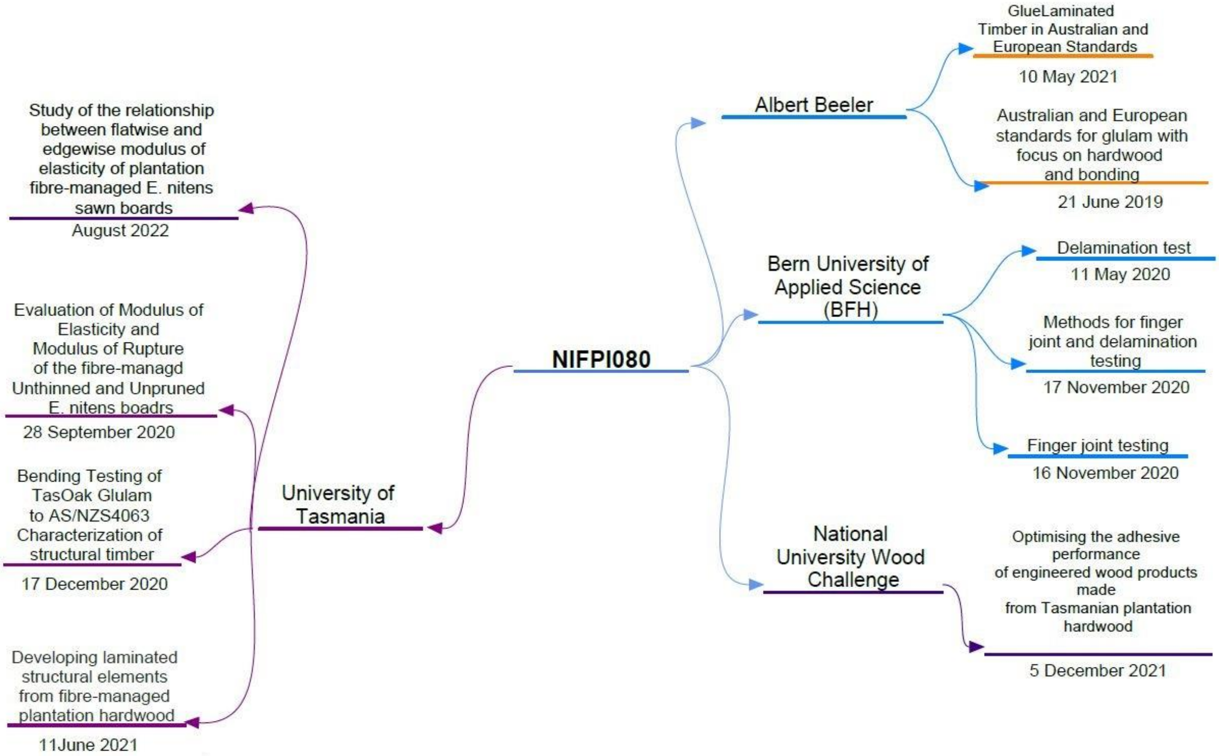
Contents

Introduction

This report outlines the glulam production work using fibre-managed plantation sawn boards in the framework of the NIFPI080 project *Developing laminated structural elements from fibre-managed plantation hardwood*.

The project aims to develop the grading, jointing and gluing expertise necessary for the production of structurally reliable glue-laminated timber (GLT) using boards from a fibre-managed plantation hardwood resource. The aim of the structural GLT production is to explore the technical feasibility and potential in utilisation of sawn structural boards recovered mostly from plantation E. nitens as a feedstock for glulam as a high-value engineering wood product. The mind map below shows the works and reports done in his project. The objectives of this project can be summarised as following:

- Understand the correlation between the NDT technique and mechanical properties of the E. nitens sawn boards feedstock.
- Sort and grade the sawn boards into structural groups based on mechanical properties.



- Investigate structurally effective glulam manufacturing method using the laminates from different structural groups.
- Manufacture glulam elements in the first stage.
- Explore means to efficiently and reliably finger joint the material into laminates for further assembly.
- Invetigate the adhesive performance of the glulam beam through delamination testing.

Figure.1 Summary of activities completed as part of NIFPI080 research

Resource assessment and grading

The first phase of the project aimed to examine the mechanical properties of the boards, evaluate the grading methods, and suggest effective and simple criteria for sorting feedstock for glulam production. The following steps were taken for this phase:

- Visual stress grading according to AS 2082-2007
- Examining the correlation between the grade-determining mechanical properties such as Modulus of Elasticity (MoE) and Modulus of Rupture (MoR) of the fibre-managed unthinned and unpruned E. nitens boards.
- Investigating potential NDT technique using acoustic wave velocity (AWV) of MoE for effective sorting of the feedstock

Based on the results, the visual stress grading using AS 2082 was not a suitable method for grading the feedstock and can restrict the use of fibre-managed plantation E. nitens resources for engineered wood products. In order to characterise the material and evaluate the mechanical properties of feedstock, 37 boards were selected randomly from the batch. The samples' mechanical properties, MoE and MoR, were determined through a simply supported four-point beam test according to AS 4063.1:2000, as shown in Figure 2. In addition, three samples were recovered from different areas of each tested board to determine the basic density and moisture content (MC) as shown in Table 1. Those samples were defect-free and have a nominal size of 70 x 35 x 25mm^3 (refer to Appendix 1).

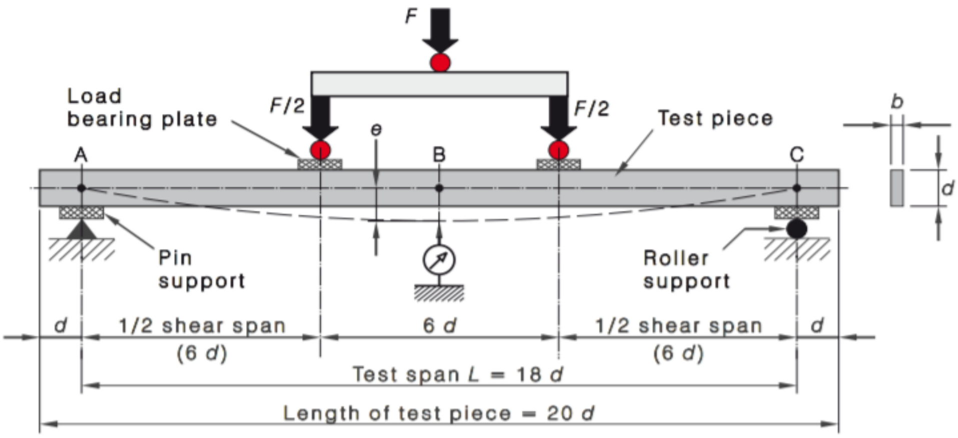


Figure 2. Static four-point bending test

In view of the NDT technique, AWV and density of the board were proven to be highly effective variables for predicting the structural quality of unthinned and unpruned *E. nitens* boards. Figure 3 shows the testing procedure of NDT technique through measuring AWV.

The dynamic MoE of the 118 boards through the NDT technique has been successfully employed to sort the plantation E. nitens feedstock into three quality groups: 37 boards to High, 42 to Medium and 39 to Low-grade group. The mean value and standard deviation of the evaluated dynamic MoE values of 118 boards are 13,042 MPa and 2,035 MPa, respectively. The dynamic MoE at the 33-percentile (11,677 MPa) and 66-percentile (13,602 MPa) of 118 samples were used as the upper limits for low- and medium-quality sorting. The results of the static four-point bending test and NDT, together with other characteristics, are presented in Table 1. The mean value and standard deviation of the static MOE and static MOR obtained by the bending test are greater than those that are obtained by the previous study of approximately 4.5 m boards with four different widths, 70mm, 90mm, 120mm and 140mm (Derikvand et al., 2018): the MOE and MOR of 55 boards range within 10.80 ± 1.88 GPa and 43.55 ± 14.37 MPa, respectively (see Table 2). This is attributed to the smaller number of samples in this test and the younger material used in the previous study (refer to Appendix 1).

Table 1. Static bending test result of E. nitens boards (70x35x2100 m^3)

Sample ID	MoE_{static} [GPa]	MoR_{static} [MPa]	Weight of board [kg]	Density [kg/m^3]	AWV [km/sec]	Moisture Content [%]	Dynamic MOE [GPa]
Max.	17.88	90.95	3.65	619.20	5.36	17.62	17.26
Min.	7.91	22.86	2.70	422.10	4.06	12.38	8.81
Mean	13.25	54.04	3.24	529.23	4.83	17.62	12.44
STD	2.50	18.47	0.26	52.69	0.31	12.38	2.29
COV	18.87	34.17	7.97	9.96	6.38	14.95	18.39

Table 2. MoE and MoR values in this study against those reported by Derikvand et al. 2018

	Size	Age	MoE (GPa)	MoR (MPa)
Test by Derikvand et al. 2018	70, 90, 120, 140 x 35 x 4500 mm^3	16	10.80 ± 1.88	43.55 ± 14.37
Test 2020	70 x 35 x 2100 mm^3	21	13.25 ± 2.5	54.04 ± 18.47

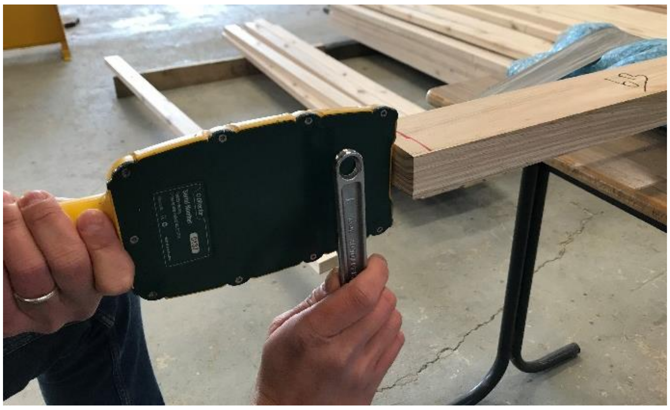


Figure 3. NDT technique testing procedure

Study of the relationship between flatwise and edgewise modulus of elasticity of plantation fibre-managed *E. nitens* sawn boards

Recently, Jian Hou and other researchers from centre for sustainable Architecture with wood have investigated the relationship between flatwise and edgewise MoE of plantation fibre-managed *E. nitens* sawn boards. They tested 331 boards to build a complete picture of this resource by measuring the density, moisture content, and static edgewise MoE. Then, 147 boards were tested for static flatwise MoE (in 100mm increments). Results showed that average static flatwise MoE is highly linearly related to static edgewise MoE. The average flatwise MoE could be predicted through the linear relationship considering the contribution of the width of the boards. The R^2 value of this linear regression formula is 0.9. The bending test results of the boards showed that the static edgewise MoE values conformed to a normal distribution (Figure 4). Potential application prospects of manufacturing mass timber products by using *E. nitens* were observed. Both density and moisture content were statically significantly correlated to the static edgewise MoE. A linear regression model was built to predict static edgewise MoE based on the density, however, the correlation coefficient $R^2 = 0.49$ was low. Even the linear combination of density and moisture content did not significantly increase the prediction quality. They claimed that although the Australian visual grade standard is inefficient in grading plantation fibre-managed *E. nitens*, visual feature groups play a role in predicting the average static flatwise MoE. Density and the visual group were statistically significantly correlated to the average static flatwise MoE. A linear regression model considering density and the visual group was built up to predict average static flatwise MoE. The prediction quality was acceptable with the correlation coefficient $R^2 = 0.77$. The relationship between edgewise and flatwise MoE was determined. Given any one of them, the other could be predicted. The prediction accuracy was high with $R^2 = 0.90$. Width has been considered because of the shear deformation. Further study could be conducted to investigate the influence of width on determining the flatwise MoE. Two test subsets were used to verify the prediction accuracy of the models. The relationship model performed better than the factor-based models for predicting edgewise or flatwise MoE. In addition, the relationship model worked well on the quarter-sawn test set (subset C). A full-scale sawing study may provide more comprehensive results in terms of comparing the sawing method of *E. nitens* (refer to Appendix 7).

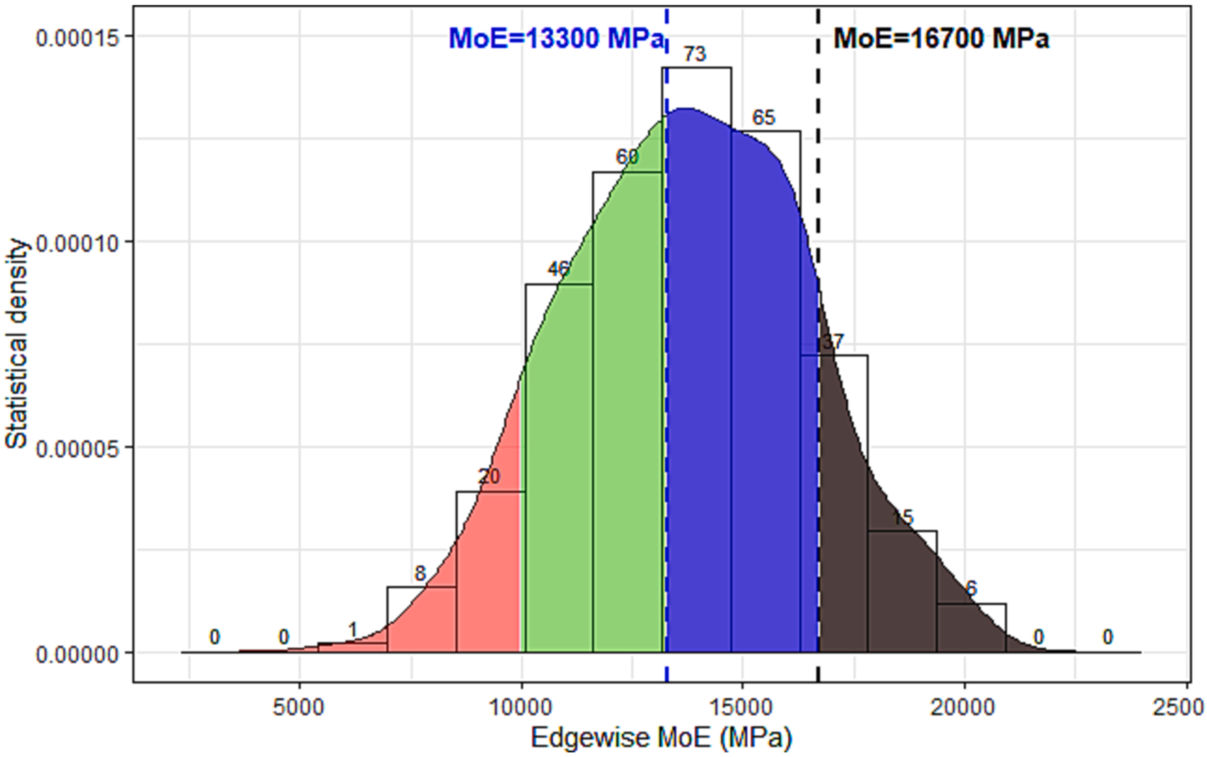


Fig. 4 Static edgewise MoE distribution (n = 331)

Manufacturing glue-laminated elements using graded feedstock

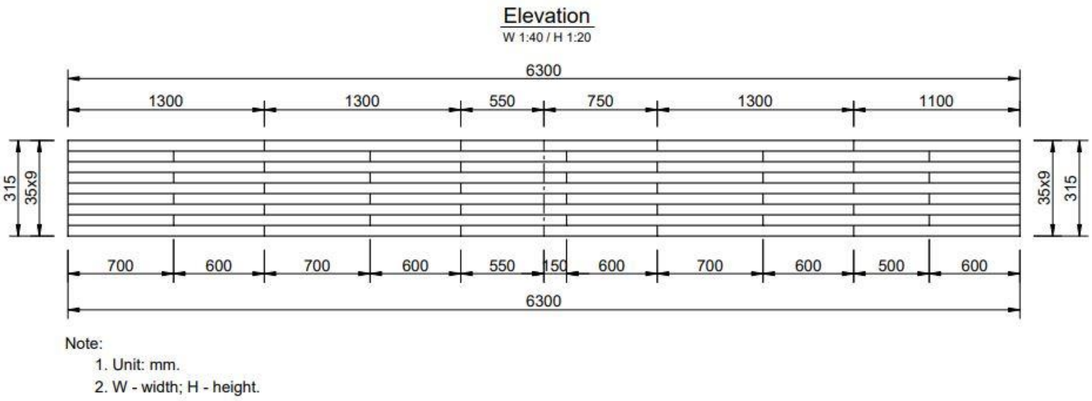
The project's next phase was to manufacture the glulam beams based on graded boards and examine the structural performance of the elements. In total, six full-size glulam samples were produced and tested under bending test to investigate the sorting feedstock by the NDE method, load-bearing capacity and failure mode. Three lay-up combinations for the 9-ply glulam beams (70x295x6000mm) were used. Figure 4 (a) illustrates an elevation of the tested beams and (b) shows the test setup of these beams. Three different lay-up combinations were applied to evaluate the static MoE and MoR with different qualities of the lamellae. The laminations of higher quality were placed in the outer six layers (three top and three bottom), and lower quality laminations were used in the middle third. The grade and position combinations were:

• Medium/Low/Medium (MLM) – Samples GNC 1, 4 and 6

• High/Low/High (HLH) – Samples GNC 3 and 5

• High/Medium/High (HMH) – Sample GNC 2

The static MoE of 6 glulam beams were determined and compared with the average dynamic MoE of the laminations in the test rig's top, middle and bottom positions. Figure 5 illustrates the MoE results of all six beams (refer to Appendix 8).



(a)

(b)

Figure 5. Elevation view of the tested beam (a), Bending test of a combined glulam sample (b)

As shown in Figure 6, it is apparent that the quality characterised by the average dynamic MoE value in the top and bottom layers are crucial in the global static MoE of the glulam element. On the other hand, the influence of the lower quality lamination in the middle third of the beam on the MoE of the glulam is marginal. This finding supports the assumption that the use of the low-quality E. nitnes feedstock in the region in the beam where lower stress occurs through bending is acceptable for producing reliable glulam elements (refer to Appendix 8).

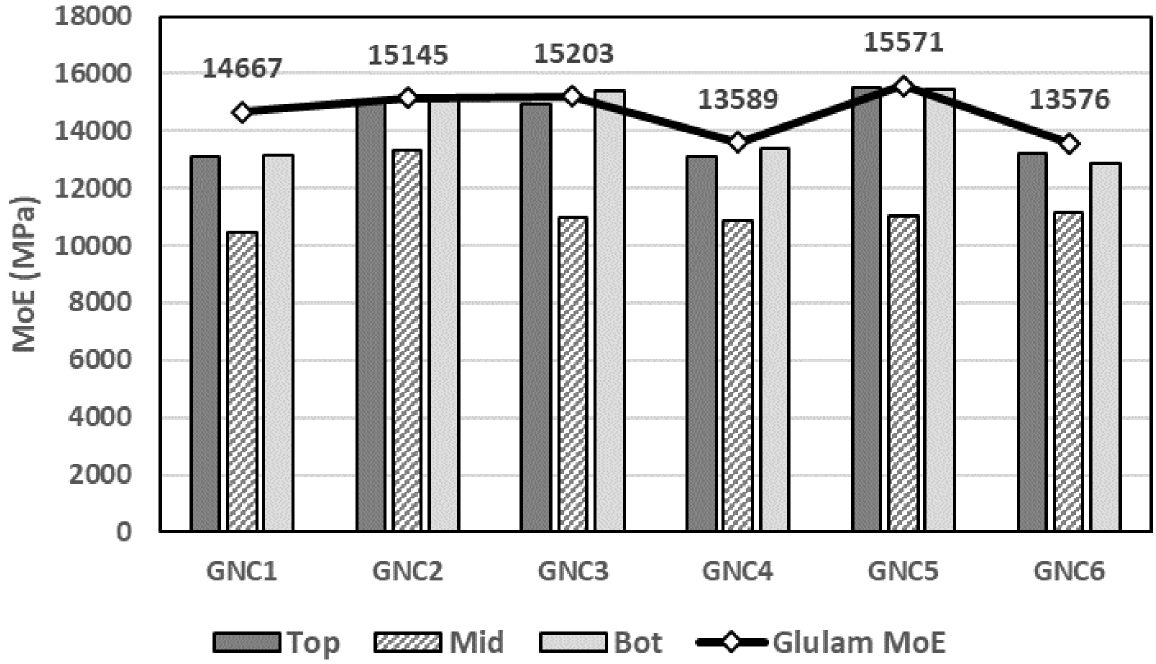


Figure 6. The result of six glulam elements and dynamic MoE of the laminations

The glulam samples with the high MoE laminations in the outer layers (GNC 2,3 and 5) show higher static MoE and MoR values than those with medium MoE boards as shown in Figure 7. All samples fell in GL13 (MoR>33 MPa, MoE>13,300 MPa) grade. The maximum and minimum static MoE value of the glulam were 15571 MPa and 13576 MPa, respectively. The maximum and minimum static MoR value were 39.85 MPa and 61.43 MPa, respectively. Three out of six samples exhibited clean failure in the finger joints. These are GNC2, GNC4 and GNC5.

Improving finger joint tensile strength could increase the bending performance of the glulam from plantation E. nitnes. Further finger joint test and delamination tests are in progress and will provide a practice guide for optimal finger joint production and face gluing (refer to Appendix 8).

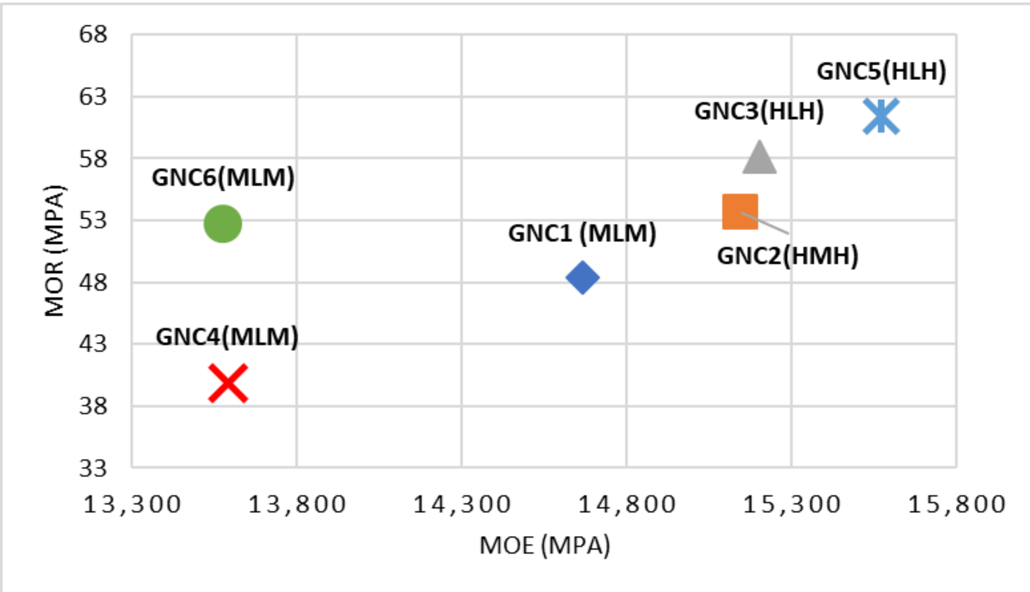


Figure 7. Static MoE and MoR of 6 glulam samples

Bending test of TasOak Glulam

In addition to the E. nitens GLT, the glulam production work using Tasoak sawn boards in the framework of the NIFPI project developing laminated structural elements from fibre-managed plantation hardwood was conducted. Five three-plyTasOak glulam beams (1815 x 100 x 70 mm) with vertical finger-joint were tested under four-point bending. The samples have vertical finger joints. Finger length and pitch are approximately 19 mm, and 4 mm, respectively (see Figure 8). The glulam elements were tested under the test methods in AS/NZS 4063.1:2010 to determine bending strength, apparent modulus of elasticity (stiffness) and shear strength. The average MoE and MoR of five TasOak glulam beams were 15458 MPa GPa and 51.4 MPa respectively (see Table 3). Sample B-3 showed shear failure in the glue line and a low MoR. The finger joints in the glulam elements exhibited a good load-bearing capacity in bending, while glue line failure was observed in two samples (B-2 and B-3). More samples need to be produced and tested to characterise the mechanical properties of the glulam from TasOak. In addition, characterisation of mechanical properties of the lamination is also required. Delamination test to determine bonding performance is required to evaluate the shear strength of the glue line and determine effective gluing practice for reliable glulam product (see Appendix 5).

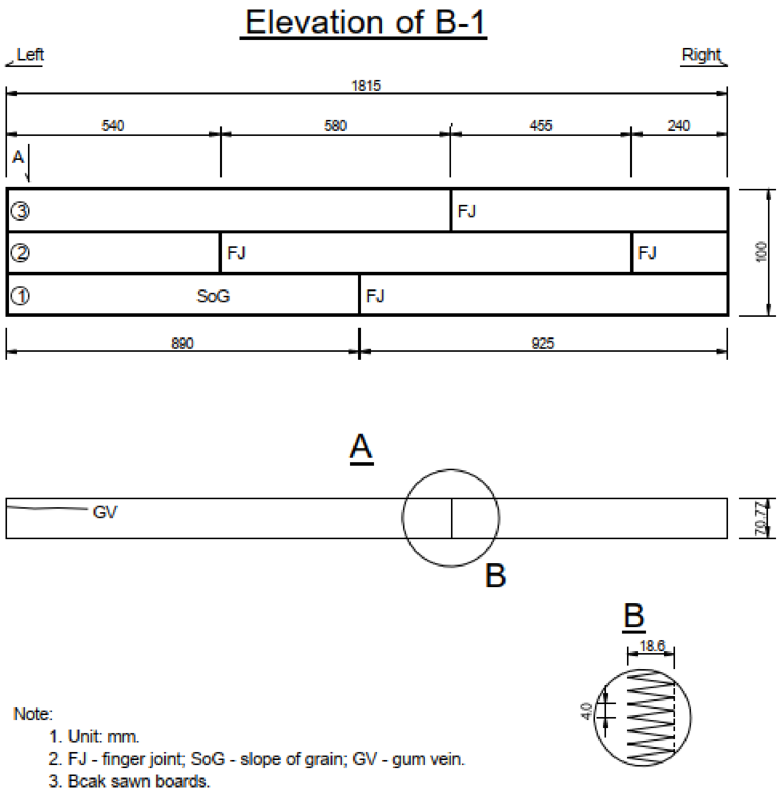


Figure 8. TasOak Glulam configuration

Table 3. Results of the four-point bending test

Sample	MoE (MPa)	MoR (MPa)	Ultimate load (kg)
A-1	16,376	53.1	2,044
A-3	15,625	62.9	2,532
B-1	14,420	56.3	2,172
B-2	15,722	55.2	2,790
B-3	15,145	29.3	1,162
Average	15,458	51.4	2,140

Means to efficiently and reliably finger joint the material into laminates for further assembly

The assessment of the feedstock was performed at Bern University of Applied Sciences (BFH) in Switzerland. The density of the joining members were determined to segregate the finger joint samples into three groups based on the density, defects on the boards, location of the planned and existing finger joint and the type of industrial jointing process to be applied. The size of the density sample is based on the requirements of the EN 13183-1 and corrected for moisture content.

From the total number of samples, 11 were selected for the determination of the moisture content. In addition, the 11 samples were selected so to represent the range of the density of the boards, which varied from 466 kg/m^3 to 717 kg/m^3. The average moisture content was 11%. The density and M.C. strips were scanned to have their growth rigs documented.

Requirements and limitations for new finger joint production and testing

For the new finger joints, a total length of at least 1 meter was required by the companies for each of the two connecting members (each side of the finger joint). This is the lower limit that the joint finger machine can handle. Also, for the process and workability, a maximum board length of 1.2 m was decided. Based on the EN 14080 & EN 408 standards requirements for the allowable position of knots in the board and the configuration of the tensile testing machine, the tensile test pieces were specified. Initially, the position of the new finger joint was chosen so that the existing finger joints and major knots in the boards would be at least 40 cm and 35 cm away from the new finger joint, respectively. The test sample for the tensile test should be at least 120 cm; 60 cm on each side of the new finger joint, 20cm clear and 40cm clamped. The sample Is then placed in two 40 cm clamps on each side, leaving a total of 40 cm in the middle unclamped (see Appendix 4).

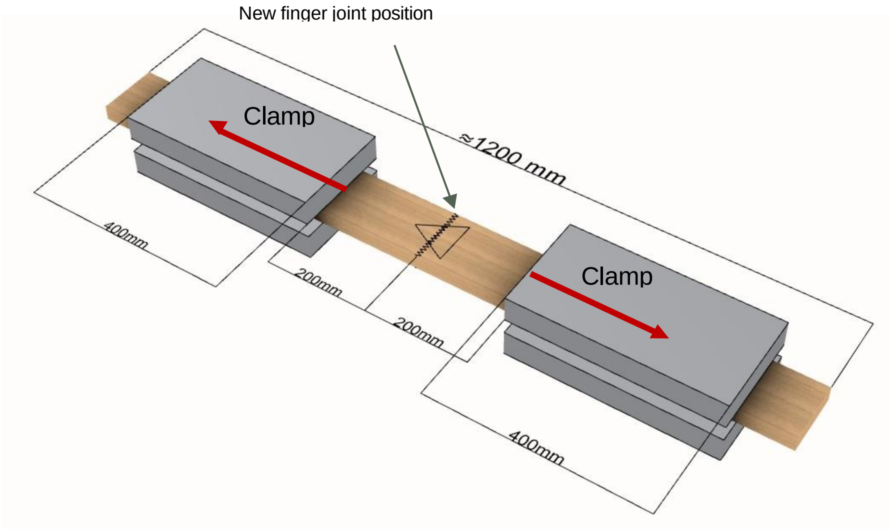


Figure 9. simplified setup of the tension test with the position of the new finger joint and the clamps

Finger joints

The boards were selected in such a way to ensure defect-free timber portions to locate the finger joints. Densities on both sides of the future finger joint have been determined and finger joints were produced by a Swiss glulam manufacturer. The pressure was adjusted to avoid crushing the fingers but ensure that the joint was closed properly.

Loctite HB S109 Purbond was used for both series and a 15/3,8 mm finger joint profile was applied. Two series with similar density distribution were produced: for series 1 the standard process for spruce was applied, for series 2 a special hardwood process developed by the glulam manufacturer was applied. Series 3 represents the finger joints produced by CLTP (now CUSP) at an earlier stage for the Dubai project. The tension tests were carried out at the laboratory of the BFH in Biel. The tests were done along EN 408:2010 & A1:2012. The exact measurements and positioning of the finger joint are shown in Figure 9. The load was applied force controlled to failure, and the speed was chosen that it could be expected that failure would occur in 300 ± 120 seconds (see Appendix 6).

Some of the specimens failed in tension in the timber section; the finger joints did not influence the failure. These specimens were not considered in the analysis, however, most failures occurred in the region of/in the finger joints and therefore represented the strength of this connection (13). The tension strength achieved by series 1 and 2 was sufficient to produce glulam with the strength class GL24 and GL28. The finger joints supplied by CLTP show clearly lower tensile strength and are not sufficient to produce structural glulam (See Figure 10 and Table 4).

Figure 10. Typical failure of the finger joints in series one and two

Table 4 shows the results from the tension tests on finger joints. For the calculation of the 5%- percentile, the number of the specimens was considered as required in EN 14358:2016 as proposed for initial type testing, assuming a log-normal distribution of the tensile strength of the finger joint. A student-test showed no significant difference between the two series produced in Switzerland. The 5%-percentile value of these two series is nearly equal; the coefficient of variation for the hardwood process is higher compared to the softwood process if the outlier in the softwood process is not considered. No grading routine could be undertaken to separate the timber forming the specimens into 2 or 3 stress grades. The results are obtained on ungraded timber. Table 4 clearly shows that the hardwood process (series 2) enables for higher tension strength than the softwood process. However, this potential can only be realised if the 5%-percentile can be increased by avoiding failure at "low" strength in optimising the MOE and density profiles of the boards.

In order to estimate the cause for the "low" values in Series 2, a larger testing campaign with stress graded boards with a finally established grading routine on the finally used resource would be necessary (stress grading criteria needed). Table 4 also clearly shows the significant difference between the finger joints produced using shorter fingers and the ones using longer fingers, both produced in Switzerland. It must be kept in mind that Schilliger Holz (Dubai project) came up with some doubts regarding the quality of gluing from this early-stage finger joint production. It can be concluded from this small test series that eucalyptus nitens has a promising potential if the right finger joint profile and the right process are used (Appendix 6).

Table 4. Overview of the results

	Series 1	Series 2	Series 3
Number of specimens considered	17	17	9
Average tension strength	43.8 MPa	48.3 MPa	18.7 MPa
5%-percentile	28.6 MPa	28.1 MPa	10.8 MPa
min	30.0 MPa	30.6 MPa	12.9 MPa
max	69.6 MPa	69.0 MPa	25.0 MPa

Adhesion assessment (face gluing)

Delamination tests proved to be an adequate method for quality control and to determine suitable adhesives with and without primer in the gluing process. It is important to investigate the bonding performance of PUR using fibre-managed plantation E. nitens and to perform delamination test to proof that bonding is adequate. For the species in question it must be shown if a pre-treatment with primer is required or not. To do so, the first delamination test is done without the use of a primer. In this way, if the delamination exceeds the limit, the use of primer could be considered to bring the delamination below the limit required by the standard.

Production of glulam specimens for delamination test

The delamination test was done based on the EN 302-2 standard. A total of 30 boards with a length of 600mm were cut out from the 3m boards, and stored in the climate room (M.C. 65%, temp 20°C) for a period of 2 weeks. Then 12 of the boards with the highest density were planed and two glulam beams were produced (180g/mm^2 of one component PUR glue) in the Energy lab at the BFH in Biel. The density range of the first glulam (G1) is from 617 kg/m^3 to 706 kg/m^3 with the average of 654 kg/m^3. The density range of the second glulam (G2) varied from 568 kg/m^3 to 609 kg/m^3 with an average of 586kg/m^3. The two glulam beams were then climatised again for two weeks (a minimum of 7 days is required by the standard) before the specimens were prepared (Figures 11 and 12).

Glulam name	Element name	Density kg/m3	Glulam name	Element name	Density kg/m3
G1	E80_D1	676	G2	E38_D1	606
	E2_D1	665		E18_D2	608
	E15_D1	630		E1_D2	590
	E17_D1	628		E72_D2	578
	E17_D2	617		E1_D1	568
	E36_D1	706		E45_D1	568

Figure 11. List of the two produced glulam beams comprising lamellas along with their densities and their cross-section after first drying

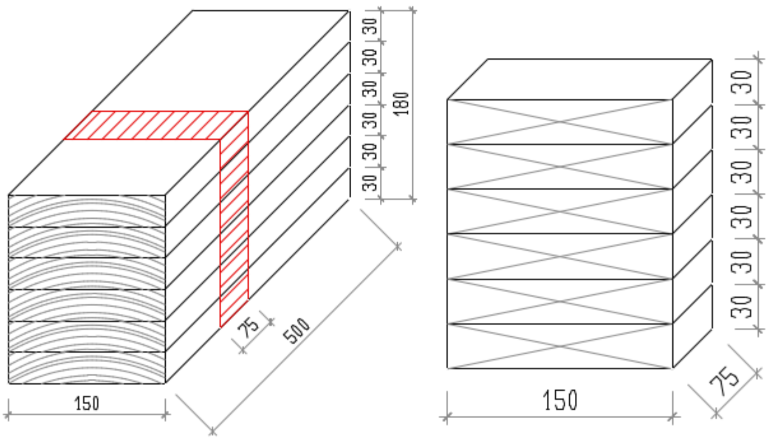
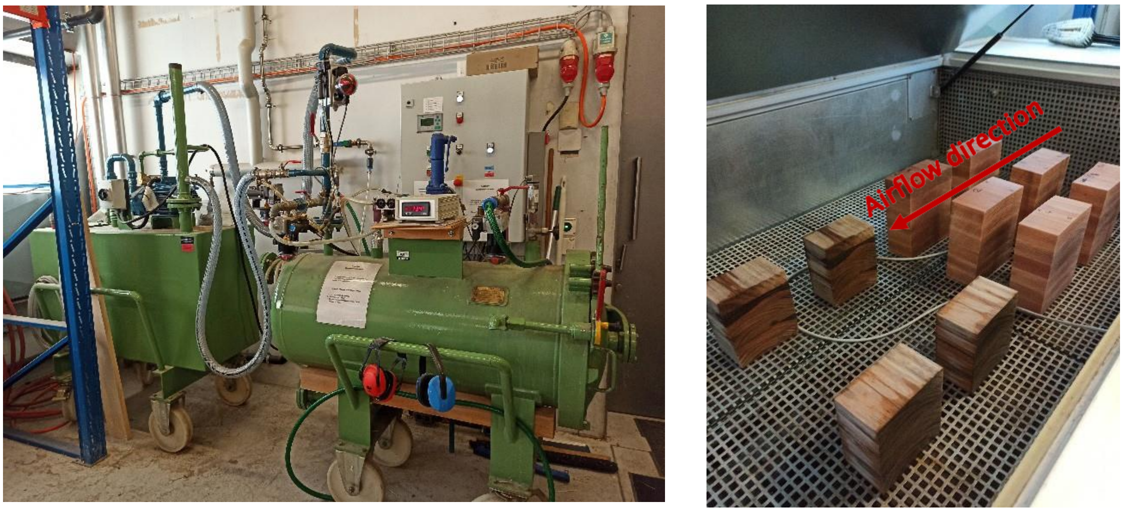


Figure 12. Laminated beam and specimen (red and right) as required by EN 302-2

Delamination test

The delamination test comprises of three set of cycles. Each cycle includes the water absorption phase and drying phase. The water absorption is done in an autoclave, Figure 13 (a). The drying is done in the dryer, Figure 13 (b), with controlled humidity and airflow speed (Appendix 3 and 4).



(a) (b)

Figure 13. Devices used in delamination test, (a) Autoclave, Air dryer with controlled humidity and airflow speed (b)

Optimising the adhesive performance of mass timber elements from Eucalyptus plantation hardwood

In addition to the tests above, a team of researchers lead by Dr Kyra Wood at the University of Tasmnia prototyped and produced three key mass timber elements using plantation *Eucalyptus nitens,* including GLT, cross-laminated timber (CLT), and finger joints (Figure 14) as part of the "National University Wood Challenge". The team undertook product prototyping and testing to enhance the bonding performance of plantation *Eucalyptus nitens* hardwood for these products. They used targeted approaches for each element by altering the glue types, pressing times, press pressures, spread rate and surface preparation treatments. Then, they tested our samples by selectively subjecting them to a series of engineering stress tests, including delamination, wet and dry block shear, bending (MoE) and rupture (MoR). To test the structural performance of our prototypes, the researchers primarily based their analytic methods on the requirements outlined in the Australian standards for manufacturing softwood GLT, AS/NZS 1328.1 and the European Standard, EN 16351. It is important to note that there is no Australian Standard for making or testing CLT and no standard anywhere in the world for CLT or GLT made from hardwoods.

This presents a significant problem for the Australian timber manufacturing industry as well as for those seeking to use engineered wood products made from hardwoods in the built environment. Based on the results of the CLT assemblies, it can be concluded that press pressure had a significant impact on enhancing the bond performance, whereas, press time and adhesive spread rate did not have a remarkable effect on percentages of delamination. It is also worth noting that increasing the glue spread rate did not improve the performance of the prototype. The results from the GLT specimens with three different glue types and different surface treatments indicated that the use of primer when using PUR glue improved the adhesion performance of *E. nitens* mass timber.

Furthermore, face milling of the sawn timber prior to gluing was found to positively affect the bonding performance compared to surface planing. In terms of shear bond strength, the highest values were recorded when using primer and PUR adhesive for assemblies. In addition to PUR, resorcinol formaldehyde adhesive demonstrated good bonding performance.

The results from the joint finger assemblies showed that a vertical finger joint has higher efficiency of MoR, but not MoE, while the use of a primer helps improve the overall finger joint efficiency of MoE, but not the MoR. Geometry also affects the bonding performance of finger joints, with longer fingers performing significantly better. Although the mean value and damage mode showed differences in glue types, there was no statistical evidence that they performed differently; however, this warrants further research (refer to Appendix 2).

(a) (b) (c)

Figure 14. GLT samples (a), CLT samples (b), and finger jointed assemblies (c)

Report on Australian and European standards for glulam with focus on hardwood and bonding

This report was completed as part of the project and provides a review and comparative analysis of the Australian and European standards regarding the glue and glue line of glue laminated (glulam) timber with a particular focus on glulam made from plantation Eucalyptus Nitens (E. Nitens). The goal of the comparison is to identify the differences between the “Australian way” and the “European way” and whether project-relevant “holes” exist in the Australian standards. In other words, because the European standards cover more aspects and tests relating to glulam than the Australian standards, this document will outline which tests should be considered that are not necessarily required by the Australian standards for glulam, but which may increase the long term credibility and thus commercial potential of E.Nitens glulam products for domestic and international markets. The standards reviewed and compared in this document are outlined in Section 3. Each comparison is explicated partly using screenshots taken directly from the standards, and followed by a conclusion, which includes recommendations about how to proceed for the above mentioned NIFPI project. The recommendations are often distinguished between project phase 1 and 2, an approach which is explained further in Section 4. The conclusions and recommendations for all the standards reviewed in this document are then summarised again in Section 4. In addition to glue and bonding tests, bending tests are also discussed in this document, because they are in some cases closely linked with bonding (e.g. tests for bending strength to test the finger joints) and because bending-test-equipment is available and ready to use at UTAS at Inveresk Campus.

Topics that were not included in this review and comparative analysis of Australian and European standards are as follows:

- CLT

- Glued solid timber
- Glulam with large finger joints
- Block glued glulam
- Nailed laminated timber
- Stress laminated timber
- Technical parameters (such as stress grading) apart from glue, bonding and bending tests
- Service class 3 according to AS 1328.1 (as only Service class 1 and 2 are envisaged for glulam in this project).

For more information please refer to Appendix 9.

Glue Laminated Timber in Australian and European Standards

This document provides a review and comparative analysis of the Australian and European building and product standards that relate to the glue and glue line performance in glue-laminated timber (glulam). It focuses on the potential for glulam made from plantation *Eucalyptus nitens* (*E. nitens*). In general, European glulam production standards are more extensive than comparable Australian standards and cover more design aspects and tests. This document outlines which European glulam production tests Australian producers should consider in addition to those required in Australian Standards. Conducting these additional tests may increase the long-term credibility and the commercial potential of *E. nitens* glulam products in domestic and international markets1. This report will firstly provide an overview of the standards (Section A. Overview of the Standards), a summary of the review of standards (Section B. Executive Summary), then list the tests that the standards include (Section C. Important Tests). Following this, there is a case study on *E. nitens* (Section D. Case study) and then a detailed review of each standard, with screenshots provided for key formulas and test methods (Appendix 2, Detailed Analysis). It is expected that for most audiences, the first three sections (A - D) will be of most use to understand the context of standards relevant to glulam products in Australia. For more information please refer to Appendix 10.

UNIVERSITY of TASMANIA

centre for sustainable architecture with wood

CSAW

NATIONAL INSTITUTE FOR FOREST PRODUCTS INNOVATION

Evaluation of Modulus of Elasticity and Modulus of Rupture of the fibre-managed Unthinned and Unpruned E. nitens boards

Dr Marcus Jungtae Noh

Dr Hui Jiao

Dr Assaad Taoum

28 September 2020

Project name

Contents

Introduction

As stage 1 task of NIFPI 080 glulam project, grading of E. nitens feedstock was carried out through a 4-point bending test. The objective of the bending test is as follows:

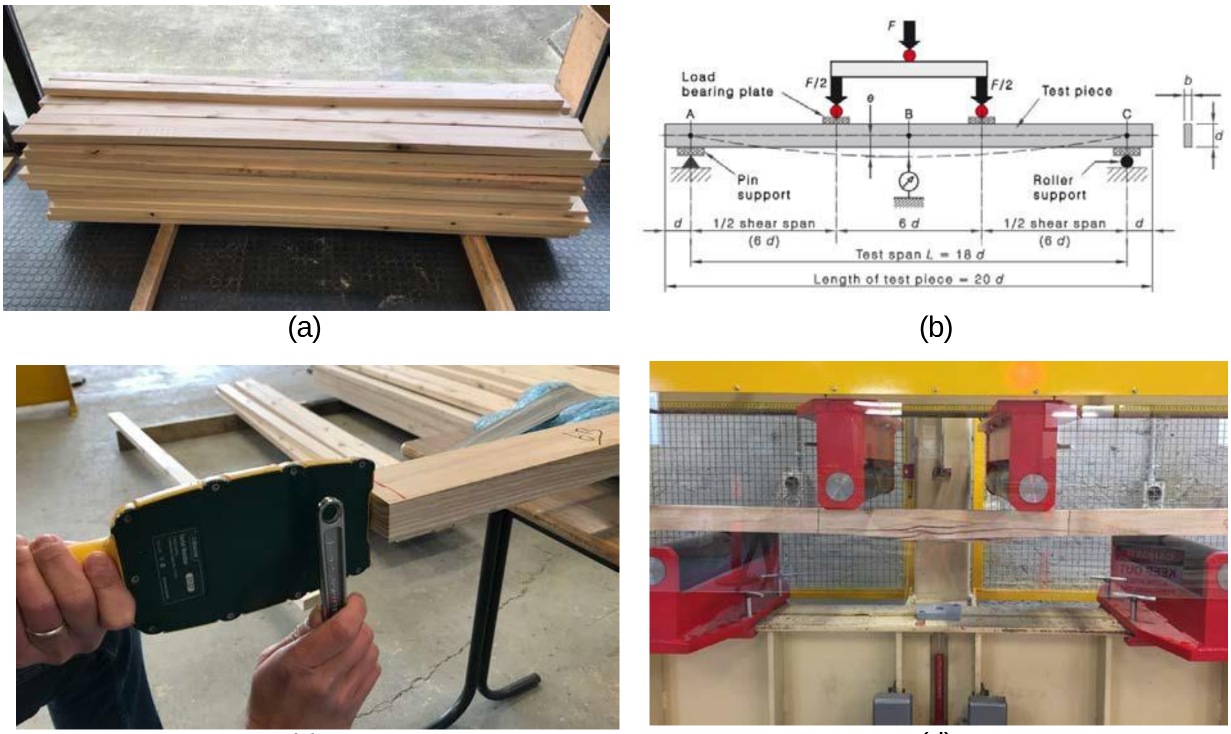
1. Examining the correlation between the grade-determining mechanical properties such as Modulus of Elasticity (MOE) and Modulus of Rupture (MOR) of the fibre-managed unthinned and unpruned *E. nitens* boards.
2. Validating visual stress grading according to AS 2082-2007
3. Investigating potential NDE approximation of MOE for effective sorting feedstock for glulam

Materials and method of testing

The impacts of the basic density, acoustic wave velocity, visual characteristics on the quality of plantation *E. nitens* boards were investigated. The information about the materials and image are provided in Table 1 and Figure 1 (a). The mechanical properties, MOE and MOR of the samples were determined through a simply supported four-point beam test according to AS 4063.1:2000, as shown in Figure 1 (b). 37 boards were selected randomly from the unknown quality batch and cut to a length equal to 20 times the width of the board. End splits, large knot holes and wane were docked off.

Table 1 Specimen data for the bending test

Material	Unthinned and unpruned plantation E. nitens
Plantation	South of Tasmania, Australia
Age	21-year old
Sawing method	Backsawn
Drying method	Air drying
Dimension	70X35X2100 m^3 (dressed and docked)
Number of specimens	37



(a) (b)

(c) (d)

Figure 1 Testing procedure

Acoustic wave velocity (AWV) is one of a suite of non-destructive evaluation tools available to the Australian sawn hardwood industry. AWV of each board was assessed using HITMAN HM200, as shown in Figure 1 (c). Taken with wood density, AWV provides a direct measure of timber stiffness. It has been shown to be a good indicator of dray wood stiffness, i.e., MOE, and has been successful in segregation of softwood for structural timber production (Tippner et al. 2016).

Three samples were recovered from different areas of each tested board to determine the basic density and moisture content (MC). Those samples are defect-free and had a nominal size of 70 X 35 X 25mm^3.

Test Result

The result of the 4-point bending test (MOE and MOR) together with weight, density and AWV are presented in Table 2. The MOE and MOR values were determined for the 37 test samples using equations (1) and (2).

$$E = \frac{23}{108}\left(\frac{L}{d}\right)^3\left(\frac{\Delta F}{\Delta e}\right)\left(\frac{1}{b}\right) \qquad \text{Eq. (1)}$$

$$f_b = \frac{F_{ult}L}{bd^2} \qquad \text{Eq. (2)}$$

where b and d are the thickness and the width of boards in mm, L is the span length in mm, ΔF is difference in the loads between 40% and 10% of the maximum load at the ultimate failure point, Δe is the difference in deflections corresponding to the 40% and 10% of the maximum load.

The moisture content of 37 boards was variable.

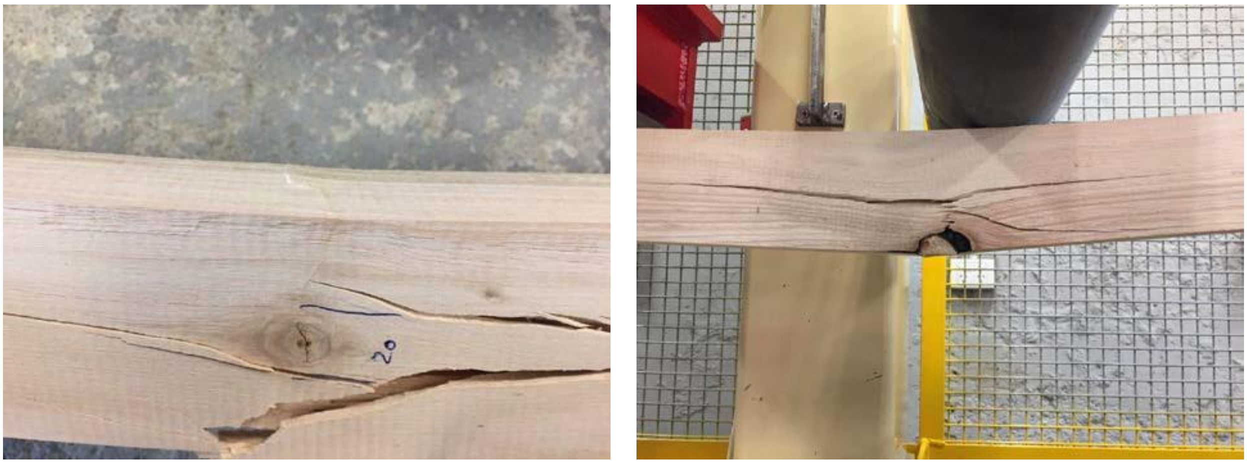
As a non-destructive evaluation method (NDE), AWV of each board was measured by HTMAN 200. The conversion of AWV into dynamic MOE is calculated by equation (3).

MMMMEEdddddd = BBBBBBBBBB ddeeddBBBBdddd x AAAAAA2 Eq. (3)

Figure 2 shows the typical failure mode of the samples at the ultimate state. Tensile failure perpendicular to the grain shown in Figure 5 (a) and (b), is predominant for most samples together with bearing/compression failure in the top compression zone (Figure 5 (c)). Tensile failure parallel to the grain was also observed in some boards (see Figure 5(d)). Most cracks were initiated above or below the major knots in the pure bending zone due to the tensile stress created between the deviated grains around the knots.

(a)

(b)



(c) **(d)**

Figure 2 Failure mode of the E. nitnes boards in bending

Table 2 Static bending test result of E. nitens boards (70X35X2100 m^3)

	Sample ID	MOE_{static} [GPa]	MOR_{static} [MPa]	Weight of board [kg]	Density [kg/m³]	AWV [km/sec]	Moisture Content [%]	Dynamic MOE [GPa]
1	6A	17.88	75.37	3.65	619.15	5.25	14.39	17.09
2	6B	16.50	90.95	3.60	619.15	4.96	14.73	15.23
3	7A	11.61	44.76	3.00	452.17	5.03	14.36	11.44
4	7B	9.87	38.06	2.80	452.17	4.50	14.23	9.17
5	8A	16.82	42.54	2.95	600.07	5.36	15.50	17.26
6	8B	15.77	72.88	2.80	600.07	5.00	16.08	15.00
7	9A	10.01	22.86	3.60	468.51	4.52	15.99	9.59
8	9B	12.98	61.55	3.40	468.51	4.98	15.59	11.62
9	10A	11.69	42.53	3.00	490.64	4.76	14.75	11.13
10	17A	16.36	81.50	3.10	567.92	5.13	13.23	14.93
11	17B	12.71	52.09	2.90	567.92	5.00	12.89	14.22
12	18A	7.91	25.48	3.65	533.06	4.24	16.19	9.60
13	18B	11.64	49.96	3.40	533.06	4.50	14.95	10.78
14	20A	12.38	38.84	3.20	556.51	4.72	14.75	12.40
15	20B	14.10	49.80	3.05	556.51	4.70	15.72	12.28
16	21A	13.98	68.42	3.15	578.67	5.12	14.62	15.17
17	21B	12.39	62.23	3.35	578.67	5.01	15.02	14.52
18	22A	9.06	40.56	3.15	480.68	4.45	14.74	9.52
19	22B	11.46	26.70	3.20	480.68	4.47	14.98	9.60
20	24A	16.52	61.27	2.70	422.13	5.07	12.38	10.87
21	24B	16.10	65.49	3.20	422.13	5.25	13.29	11.65
22	25A	10.04	30.93	3.60	468.58	4.34	13.90	8.81
23	26A	12.45	30.18	3.00	499.45	4.83	13.25	11.67
24	26B	14.50	78.69	3.30	499.45	4.97	13.69	12.35
25	27A	15.70	70.67	3.40	571.30	5.29	13.57	15.99
26	27B	17.76	86.57	3.50	571.30	5.20	14.83	15.47
27	28A	11.28	52.84	2.90	495.42	4.65	14.60	10.70
28	28B	12.77	24.72	3.35	495.42	4.50	15.21	10.02
29	30A	14.84	67.38	3.35	538.61	4.99	14.95	13.39
30	30B	13.60	77.56	3.30	538.61	4.78	15.66	12.31
31	71A	15.43	75.35	3.50	567.31	4.95	17.09	13.92
32	71B	13.11	51.11	3.25	567.31	4.75	15.40	12.78
33	92B	11.16	45.36	3.35	572.15	4.68	15.00	12.51
34	96A	13.60	49.65	3.30	560.92	4.93	16.63	13.61
35	96B	9.85	34.55	3.65	560.92	4.06	16.21	9.25
36	97A	11.47	56.87	3.05	513.14	4.70	17.05	11.34
37	97B	12.92	53.15	3.10	513.14	5.05	17.62	13.07
Max.		**17.88**	**90.95**	**3.65**	**619.20**	**5.36**	**17.62**	**17.26**
Min.		**7.91**	**22.86**	**2.70**	**422.10**	**4.06**	**12.38**	**8.81**
Mean		**13.25**	**54.04**	**3.24**	**529.23**	**4.83**	**17.62**	**12.44**
STD		**2.50**	**18.47**	**0.26**	**52.69**	**0.31**	**12.38**	**2.29**
COV		**18.87**	**34.17**	**7.97**	**9.96**	**6.38**	**14.95**	**18.39**

Discussion

Predicting mechanical properties

Modulus of Elasticity

The results of the static 4-point bending test and non-destructive testing together with other features are presented in Table 2. The mean value and standard deviation of the static MOE and static MOR obtained by the bending test are greater than those that are obtained by the previous study of approximately 4.5 m boards with four different widths, 70mm, 90mm, 120mm and 140mm (Derikvand et al., 2018): the MOE and MOR of 55 boards range within 10.80 ± 1.88 GPa and 43.55 ± 14.37 MPa, respectively (see Table 3). This is attributed to the smaller number of the samples in this test and younger material use in the previous study.

Table 3 MOE and MOR values in this study against those reported by Derikvant et al. 2018

	Size	Age	MOE (GPa)	MOR (MPa)
Test by Derikvant et al. 2018	70, 90, 120, 140 X 35 X 4500 mm^3	16	10.80 ± 1.88	43.55 ± 14.37
Test 2020	70 X 35 X 2100 mm^3	21	13.25 ± 2.5	54.04 ± 18.47

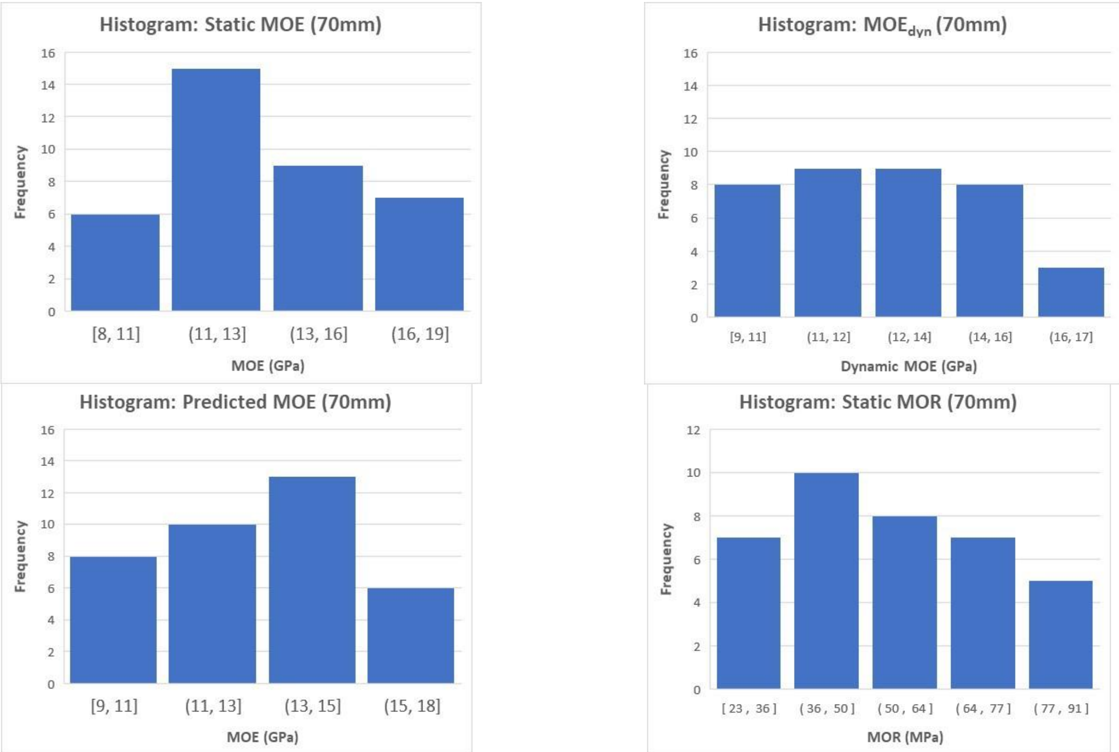
The dynamic MOE is calculated using Equation (3). Distribution of static MOE, dynamic MOE and static MOR are illustrated in Figure 3 (a), (b) and (c). It is noted that the range of the static MOE values is in a good agreement with that of the dynamic MOE determined by using the density and AWV squared of each board as shown in Figure 4 (a). The mean value and standard deviation of dynamic MOE is 5.7% and 8.5% smaller, respectively than those of static MOE values. The underestimated dynamic MOE values compared to the static MOE can be explained by the decrease of AWV due to the average moisture content of the tested samples higher than 12 % (mean MC: 14.95%).

The Pearson correlation coefficient (R-value) between static MOE and dynamic MOE is 0.8. This significant correlation indicates that the reading AWV of an *E. nitens* sawn board can be an effective predictor of the stiffness of the plantation hardwood timber. This finding also sheds light on the possible non-destructive evaluation for grading the plantation *E. nitens* boards for structure purpose. Farrell et al. conducted a similar study on sorting *E. nitnes* logs using AWV (2012) and also showed the effectiveness of the AWV for segregating the logs into MPG equivalent grades.

The correlation between the timber's mechanical properties and other variables obtained from 37 boards are summarised in Table 4. The statistical significance level between variables is evaluated using Pearson's correlation coefficients and *p-value*. In this study, it is assumed that if the *p-value* between two variables is not greater than 0.05, two variables are significantly correlated with each other since the 0.05 score means the probability that no correlation exists is 5%. The R-value marked with asterisks in Table 4 indicate the statistical significance level of correlation. Other correlations among the variables obtained from the static bending test are illustrated in Appendix A. A significant correlation is observed between static MOE and dynamic MOE, static MOR, density, and AWV. Figure 4 (b) illustrates that the AWV is a key variable to estimate static MOE. This means that AWV can also be used alone to segregate the *E. nitens* boards in case measurement of basic density is not available in the mill.

For more accurate prediction of static MOE, a fitting technique, linear regression was used to investigate how closely the available data such as density and AWV can estimate the static MOE values of the timber boards. Using multiple linear regression (MLR), as known simply as multiple regression, the static MOE can be approximated using a linear combination of the weighted values of the basic density and AWV of each board. From 37 samples, the linear equations for predicting static MOE are presented in Table 5. The percentage of the considered variable variation in the last column shows how close the predicted MOE values from the considered variables in the first column are to the fitted regression line calculated by the regression equations in the second column. The relationship between static MOE and predicted MOE from the basic density and AWV (the last equation in Table 5) is exhibited in Figure 4 (c). As shown, a combination of weighted density and AWV of each board can effectively predict the static MOE since the linear model from two variables, density and AWV can explain 75% of the actual MOE values from the testing.

The 3-dimensional scatter plot of the predicted MOE data is shown in Figure 4 (d). In the 3D plot, the contoured mesh shows the regression plane in the space constructed with predicted MOE, density and AWV. The data points of predicted MOE are positioned close to the regression plane determined by the multivariable regression. The prediction using the two variables outperformed the simple linear regression models with a single variable. Comparison of static and dynamic MOE value to MGP grade characteristic stiffness are also exhibited in Figure 4 (a) and (c). The lower bound stiffness values for MGP 10, 12 and 15 grade are 10 GPa, 12.7GPa and 15.2 GPa and displayed at vertical dashed lines. By the estimated MOE values, most plantation *E. nitens* boards are sorted into MGP 10 and MGP 12 grade while 81% of the samples can not be used for a structural member as per the visual stress grading criteria of AS 2082. This will be further discussed in the next section.



(c) (d)

Figure 3 Histogram of key mechanical properties of the 70mm boards: (a) Static MOE, (b) Dynamic MOE and (c) Predicted MOE and (d) Static MOR

Table 4 *Pearson's correlation coefficients* among the variables for 37 boards

	MOE	MOE_dyn	MOR	Density	AWV	MC
MOE		0.80**	0.78**	0.41*	0.84**	-0.23
MOE_dyn			0.69**	0.76**	0.83**	-0.04
MOR				0.43**	0.69**	-0.12
Density					0.28	-0.26
AWV						0.26
MC						

*= $P < 0.05$, **= $P < 0.01$

Table 5 Linear regression equations for predicting static MOE from the variables

Variables	Regression equation (MOE in MPa)	The percentage of the response variable variation
Basic density	$MOE_1 = 3459.7+17.39\ x_1$	17%
AWV	$MOE_2 = 20640+6905.8\ x_1$	71%
Dynamic MOE	$MOE_3 = 2197.2+0.8404\ x_1$	33%
Basic density & AWV	$MOE_4 = -22629.01+8.8667\ x_1 + 6446.39\ x_2$	75%

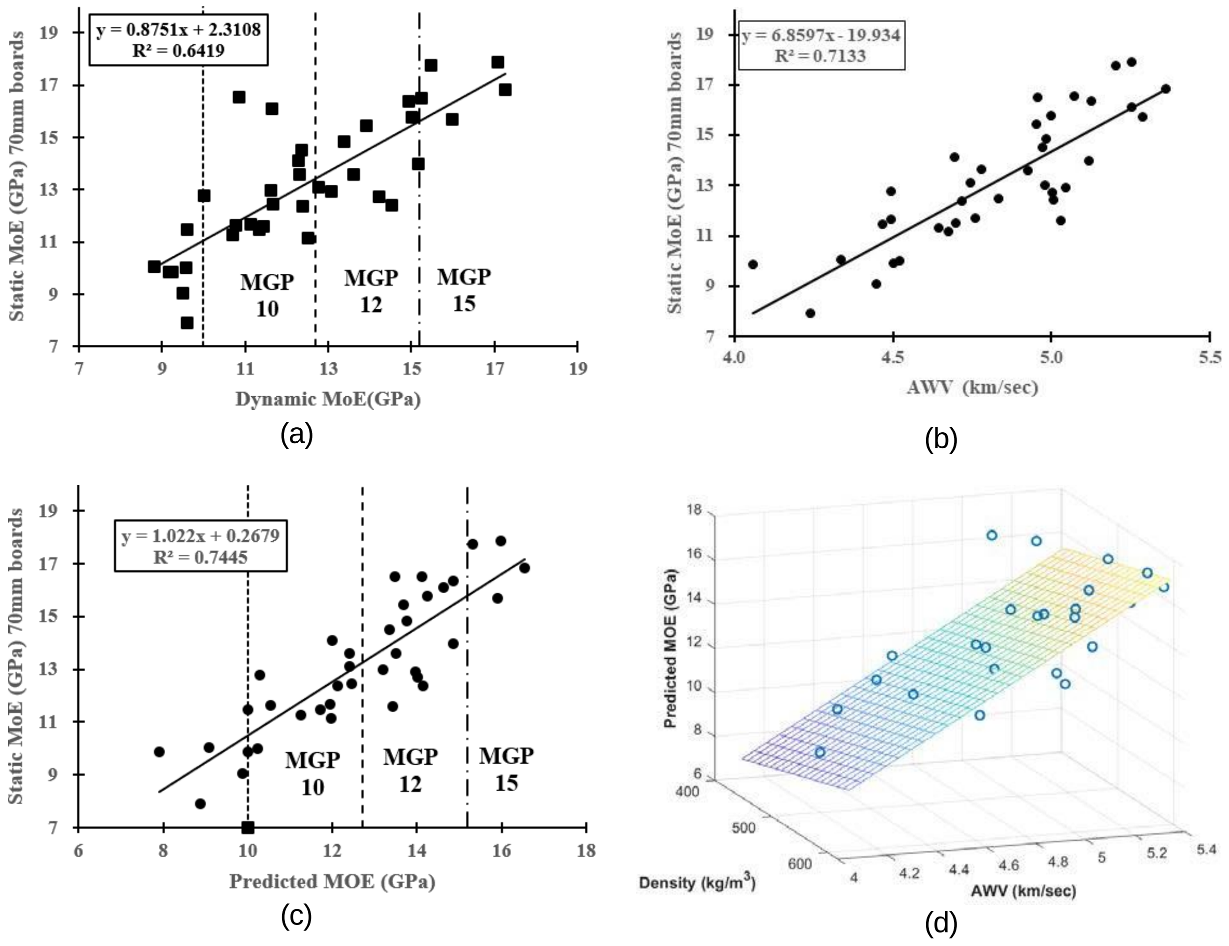


Figure 4 Linear regression model to predict static MOE

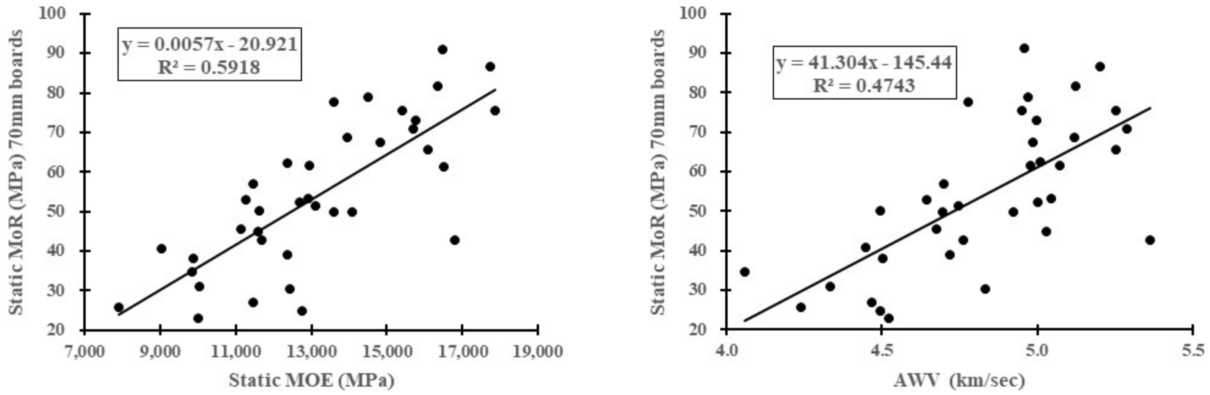
Modulus of Rupture

As a measure of bending strength, MOR values of 37 plantation E. nitens boards were investigated by applying load up to ultimate failure state and using Equation (2) from AS 4063.1:2000. The MOR values obtained from the bending test were also adjusted, taking into account the moisture content of each board. Static MOR values of 37 boards show considerable variability (coefficient of variation: 34.17). It is likely attributed to presence, frequency, types and location of the strength reducing characteristics such as knots, grain deviation and check, and the associated failure mode accordingly. MOR values estimated by this test is 24% greater than those obtained using a younger resource (Derikvant et al., 2018) as presented in Table 3. This increase in strength can also be explained by age.

Predicting the MOR values of plantation *E. nitens* was attempted using the linear regression from static MOE, AWV and density of each board. As presented in Table 4, those variables are highly correlated with static MOR values. From 37 samples, the linear equations for predicting static MOR are presented in Table 6. The relationship between static MOR and static MOE and between static MOR and AWV is shown in Figure 5 (a) and (b). The predicted MOR values from the linear equations in Table 6 are displayed against the static MOR values from the testing in Figure 6. It is apparent that the prediction using three key variables (static MOE, basic density and AWV) is more precise than those from single or two variables. However, the difference in R-squared values between different prediction is not significant. This implies that predicting MOR of plantation E. nitens is more difficult than predicting MOE.

Table 6 Linear regression equations for predicting static MOR from the variables

Variables	Regression equation (MOR in MPa)	The percentage of the response variable variation
Static MOE	$MOR_1 = -20.921+0.0057\,x_1$	59.2%
AWV	$MOR_2 = -145.44+41.304\,x_1$	48.1%
MOE and density	$MOR_3 = -40.39+0.0053\,x_1 + 0.0469\,x_2$	60.7%
MOE and AWV	$MOR_4 = -49.664+0.0048\,x_1 + 8.3095\,x_2$	59.7%
MOE, density and AWV	$MOR_5 = -77.957+0.0042\,x_1 + 10.3\,x_2 + 0.052\,x_3$	61.5%



(a) (b)

Figure 5 Relationship between static MOR and static MOE(a) and between static MOR and AWV (b)

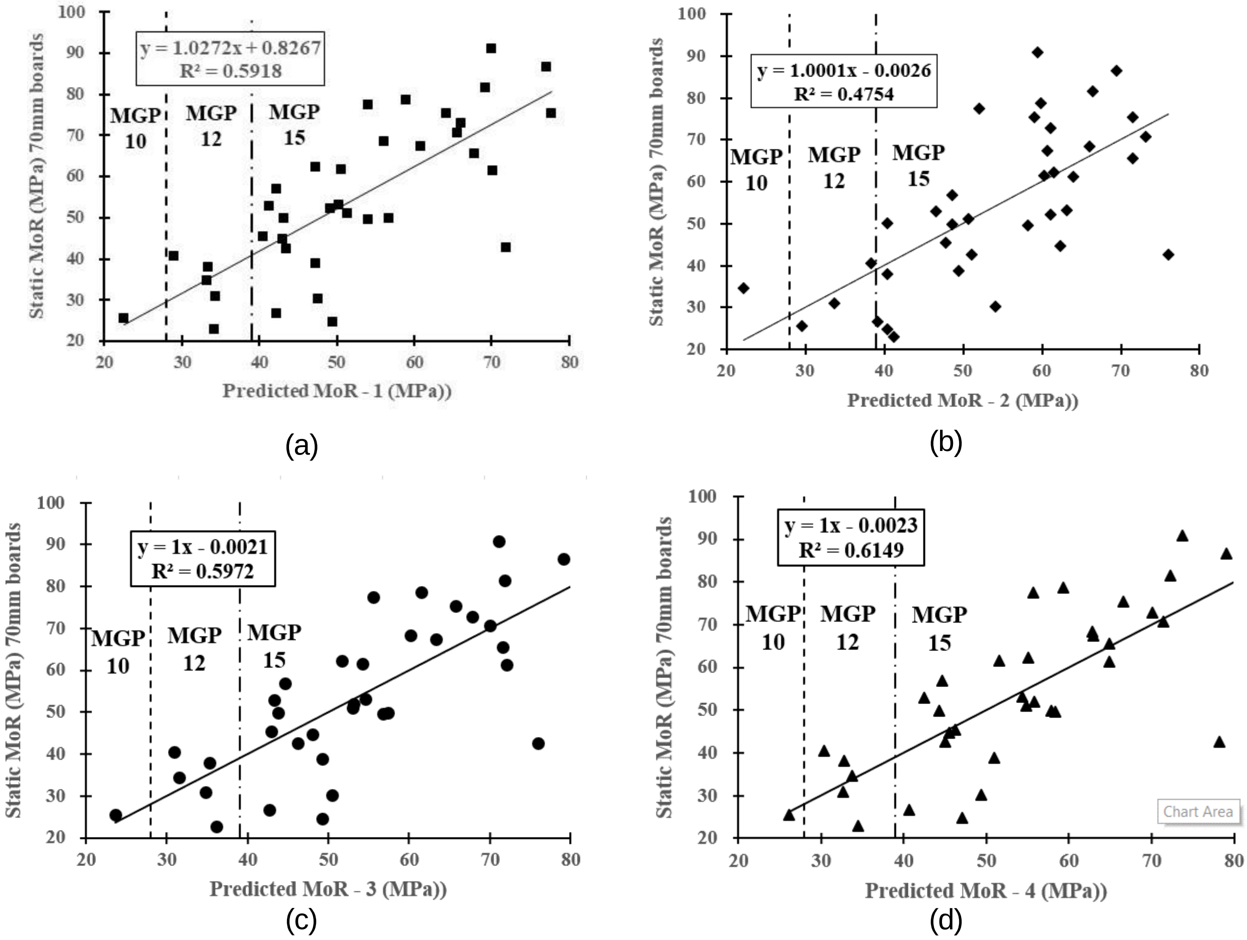


Figure 6 Predicted MOR values using the linear regression equations

Validation of visual stress grading method

Visual stress grading of the sample boards was performed in accordance with AS 2082-2007 *Timber-Hardwood-visually stress-graded for structural purposes* before the bending test. As per Table A1 Seasoned hardwood species in AS 2082-2007, the stress grades of the seasoned *E. nitens* timber with strength group of SD4 fall into four structural grades ranging from F11 to F22 (see Figure 7).

Table D1, *Summary table of grade descriptions for structural hardwood* in AS 2082 provides detailed visual grading criteria to determine the properties of the hardwood species. As summarised in Table 7, 30 out of 37 boards did not meet the criteria of the lowest structural grade (No. 4) due to the size of the existing knot diameter on either face of edge of the sawn boards. The out-of-grade boards usually contain edge knots with a large diameter. This indicates those that fail in meeting grade No. 4 (F11 equivalent) are very likely to exhibit MOE smaller than 10.5 GPa as presented in Table H2.1 of AS 1720.1-2010 *Design methods for timber structures*, but 84% of the evaluated static MOE is greater than 10.5 GPa. It is apparent that the grade determined by AS 2082 is significantly underestimated compared to the actual MOE determined by the bending test. This discrepancy is further examined using the other visual characteristics registered more specifically such as Knot- diameter ratio (KDR), arris and edge knots, the number of knots and type of knots.

gum, shining Eucalyptus nitens	S	670	A	SD4	F22	F17	F14	F11

Figure 7 Stress grades and strength groups of seasoned *E. nitens* in AS 2082-2007

Table 7 Visual stress grading according to AS 2082-2007

AS 2082 Structural grade	Number of samples
No.1	2
No.2	5
No.3	0
No.4	0
Out of grade	30

In addition to the type of visual characteristics specified in AS 2082-2007, more knot features in the 2-m-long *E. nitens* boards were assessed as presented in Table 8. The sound and dead knot mean tight and encased knot, respectively. The bending zone refers to the area between two intermediates loading points where the section subject to bending moment without internal shear force (6d in the middle in Figure 1 (b)). Knot Diameter Ratio (KDR) is a ratio of the maximum diameter of a knot measured perpendicular to the longitudinal direction of the board to the width of either face or edge of the board.

The correlation between knots characteristics and static MOE and MOR are examined in terms of the *p-value*. The result is presented in Table 9. Most knot-related variables do not show a significant level of correlation except for that between static MOR and the number of dead knots in the bending zone. This can be explained by the lower ultimate strength of the board that is attributed to stress concentration in the reduced of cross-section area due to the encased (dead) knots.

The difference in the influence of the maximum diameter on face and edge on the static MOE and MOR is marginal, as shown in Table 10. Table 11 presents the influence of arris and edge knots on the static MOE and MOR. Change in static MOE value is negligible while static MOR value of the boards 7% greater than those with arris and edge knots. However, the knot-related characteristics are not determining factors to the structural grades of the plantation hardwood samples.

Table 8 Knot characteristics of the *E. nitens* samples

Sample	No. of arris/edge knots	Total No. of knots in the bending zone	No. of sound knots in the bending zone	No. of dead knots in the bending zone	No. of knots in the bending zone	KDR
6A	2	5	0	2	2	0.71
6B	3	5	1	1	2	0.50
7A	0	8	0	3	3	0.50
7B	0	5	0	1	1	0.29
8A	0	5	0	2	2	0.36
8B	0	3	0	1	1	0.29
9A	0	4	0	1	1	0.14
9B	1	3	1	0	1	0.39
10A	3	6	2	1	3	0.69
17A	0	4	0	1	1	0.50
17B	1	7	1	3	4	1.00
18A	0	4	0	2	2	1.00
18B	1	4	0	1	1	0.57
20A	4	9	1	1	2	1.00
20B	1	6	2	0	2	0.46
21A	0	2	0	0	0	0.14
21B	0	2	0	1	1	0.29
22A	9	3	1	0	1	0.36
22B	0	9	1	4	5	0.64
24A	1	0	0	0	0	0.57
24B	4	4	1	0	1	1.00
25A	3	7	1	1	2	0.57
26A	0	2	0	1	1	0.29
26B	0	7	1	0	1	0.50
27A	0	3	0	0	0	0.29
27B	0	4	0	1	1	0.50
28A	1	2	0	0	0	0.91
28B	1	5	0	1	1	0.57
30A	0	6	0	1	1	0.71
30B	0	6	2	1	3	0.43
71A	0	9	0	2	2	0.36
71B	0	2	0	1	1	0.14
92B	0	7	0	1	1	0.43
96A	0	7	0	3	3	0.50
96B	1	3	0	2	2	0.50
97A	2	6	0	2	2	0.71
97B	0	3	2	0	2	0.17

Table 9 *p-value* between knots characteristics and mechanical properties

	KDR	Total No. of knots in the bending zone	No. of dead knots in the bending zone	No. of sound knots in the bending zone	No. of arris/edge knots
MOE	0.817	0.249	0.333	0.683	0.320
MOR	0.690	0.134	0.083	0.891	0.571

Table 10 Influence of the location of the largest knot

	The largest knot on the face		The largest knot on the edge	
	MOE	MOR	MOE	MOR
Mean value	13.16 GPa	52.66 MPa	12.37 GPa	56.68 MPa
p-value	0.235	0.801	0.273	0.305

Table 11 Influence of the arris and edge knots on MOE and MOR

	Samples with arris or edge knots		Samples without arris or edge knots	
	MOE	MOR	MOE	MOR
Mean	12.45 GPa	49.82 MPa	12.80 GPa	53.32 MPa
Standard deviation	2.54	16	2.38	19
Coefficient of variation	20.41	32.13	18.61	35.60

Conclusion

4-point bending test of 37 fibre-managed unthinned and unpruned plantation *E. nitens* boards serves three purposes: 1) determining static MOE and MOR of the feedstock for glulam, 2) validating visual stress grading according AS 2082-2007 and 3) suggesting the effective and simple criteria of sorting feedstock for glulam.

The results of the bending test and NDE of MOE using AWV show that visual stress grading using AS 2082 significantly underestimates the MOE and MOR of the timber boards. This unsuitability of the standard for plantation hardwood species can restrict the use of fibre-managed plantation *E. nitens* resource for engineered wood products

In view of the NDE for grading, AWV and density of the board are proven to be highly effective variables to predict the structural quality of unthinned and unpruned *E. nitens* boards. The approximated MOE values calculated by MLR demonstrated an excellent agreement with the actual MOE values of each board obtained by the bending test. The test also revealed that without measuring density which is a time-consuming procedure, AWV alone could be used to predict the stiffness property of the board. Thus, measuring AWV of the boards longer than 2 m in the production mill will facilitate sorting practice prior to lamination of feedstock for glulam and cross-laminated timber products.

The limitation of this study rises from a small number of samples. The correlation between knot- related visual characteristics and feedstock quality needs to be further investigated to supplement the grading feedstock process since it appears that the edge and arris knot might affect the strength of the boards and failure mode. On top of that, the linear regression equations to approximate the MOE and MOR will be refined with more sample observation. The following tasks are required for reliable glulam production using plantation *E. nitens*:

1. Determining the maximum dimension of knots in the laminate to be docked
2. Predicting MOE and MOR of full-length boards using AWV and weight
3. Establishing optimal finger joint production procedure
4. Ascertaining bonding performance of face gluing
5. Examining efficient use of resource in the full-length glulam samples
6. Producing full-length glulam samples with finger joints and qualification test
7. Providing industry with a guideline for structurally reliable glulam production

Appendix A: Correlation between the variables

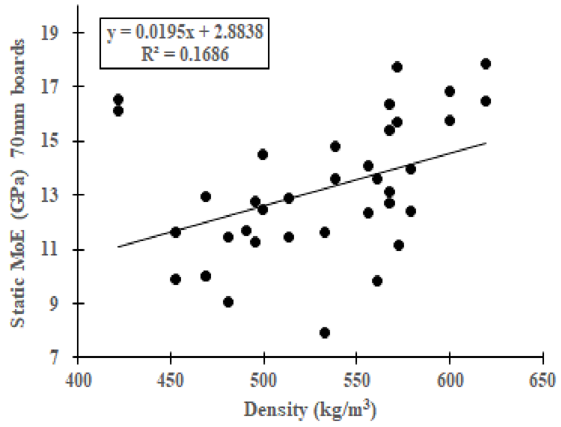


Figure A1 Correlation between MOE and density

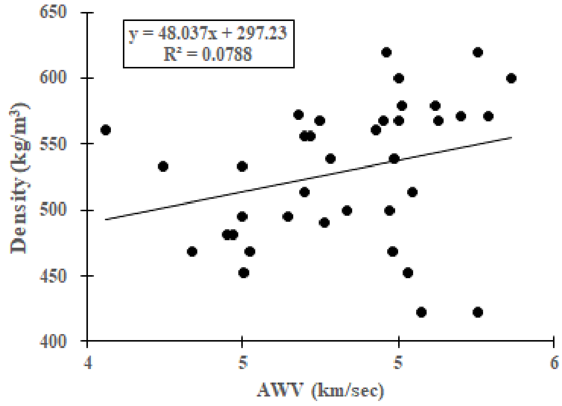


Figure A2 Correlation between density and AWV

Reference

AS 2878 (2000) Timber-Classification Into Strength Groups (Sydney: Standards Australia).

AS 4063.1 (2010) Characterisation of Structural Timber, Part 1: Test Methods (Sydney: Standards Australia)

M. Derikvand, N. Kotlarewski, M. Lee, H. Jiao, A. Chan, G. Nolan, Visual stress grading of fibre- managed plantation Eucalypt timber for structural building applications, Construction and Building Materials 167 (2018) 688–699.

J. Tippner, J. Hrivnak and M. Kloiber, Experimental evaluation of mechanical properties of softwood using acoustic methods, Acoustic tests of wood, BioResources 11(1) (2016) 503-518.R.

Farrell , Trevor C. Innes & Christopher E. Harwood (2012) Sorting Eucalyptus nitens plantation logs using acoustic wave velocity, Australian Forestry, 75:1, 22-30.

Optimising the adhesive performance of engineered wood products made from Tasmanian plantation hardwood

Executive summary and report for the National University Wood Challenge

Authors:

Dr Kyra Wood Ms

Azin Ettelaei Ms

Jian Hou

with editorial input from: Mr

Stuart Meldrum

Dr Assaad Taoum

Award title: National University Wood Challenge

Project team: University of Tasmania

Project title: Optimising the bonding performance of fibre-managed Tasmanian plantation hardwood

Project numbers: Gov153-2122 (FWPA) / WOO29173 (UTAS)

Funding body: Forest and Wood Products Australia Limited (FWPAL)

Report due date: 5 December 2021

Contents

Executive Summary

Problem statement:

Gluing fibre-managed plantation *Eucalyptus nitens* (a hardwood) to make structural timber elements is a new frontier in the global timber industry. Very little is known about the characteristics of the material or how it bonds when different adhesives, processing parameters, or surface treatments are applied. Our goal for the challenge, was to establish the optimal adhesive type, parameters and processes for making engineered wood products from Tasmanian plantation *Eucalyptus nitens*.

Approach:

First, we prototyped and produced three key mass timber elements using plantation *Eucalyptus nitens*:

- glued laminated timber (GLT)
- cross laminated timber (CLT), and
- finger joints

We used targeted approaches for each element by altering the glue types, pressing times, press pressures, spread rate and surface treatments. Then, we tested our samples by selectively subjecting them to a series of engineering stress tests, including delamination, wet and dry block shear, bending (MoE) and rupture (MoR).

Key findings:

From the GLT tests we learned that:

- face milling and using a primer prior to gluing had a significant effect on enhancing the bonding performance; resorcinol formaldehyde (RF) demonstrated a good bonding performance; and a higher spread rate (effectively, a greater amount of glue) did not improve the overall performance

From the CLT test we learned that:

- press pressure significantly influences the bond line failure, whereas spread rate and pressing time does not have a significant effect on delamination or shear failure

And from the finger joint test we learned that:

- vertical finger joints performed better than horizontal finger joints in MoR, but not in MoE; primer helps improve the finger joint efficiency in MoE, but not in MoR; and longer finger joint geometry performed better in general.

Overall, our findings reveal important new information for product and process optimisation for any industry looking to make mass timber elements from the abundant plantation *Eucalyptus nitens* resource.

Next steps:

If we win this challenge, we will use the funds to upscale this trial to validate our results, potentially apply for a patent through UTAS Holdings (and/or work with interested industry partners to do so), and seek peer review through a scientific publication in a relevant journal.

Primary research team:

Dr Kyra Wood, principal researcher Ms

Azin Ettelaei

Ms Jian Hou

Mr Stuart Meldrum Dr

Assaad Taoum

Report

Introduction

Our team

Our team is from the University of Tasmania's Centre for Sustainable Architecture with Wood (CSAW). The primary team members include principal researcher and postdoctoral fellow, Dr Kyra Wood, PhD candidates, Ms Azin Ettelaei and Ms Jian Hou, senior technical officer, Mr Stuart Meldrum, and senior engineering lecturer, Dr Assaad Taoum.

Research Questions and Approach

For the challenge we undertook product prototyping and testing to enhance the bonding performance of plantation *Eucalyptus nitens* hardwood for engineered wood products like glued laminated timber (GLT) and cross laminated timber (CLT).

The idea for this project arose out of recent research undertaken by team members, Azin Ettelaei and Jian Hou (see Figure 1), which indicated that when subject to high pressure loads, CLT and GLT samples made from fibre-managed *E. nitens* were failing frequently along bond lines and at finger joints (Ettelaei et al., 2021). Their research raised several important questions about the bonding characteristics of fibre-managed *E. nitens* and helped us establish the need to improve adhesive performance and processes.

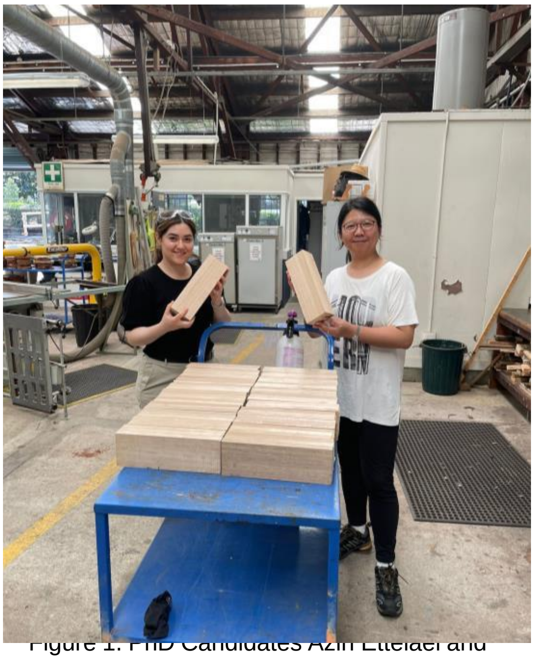


Figure 1. PhD Candidates Azin Ettelaei and Jian Hou at DAF research facility holding some of our prototype GLT samples.

First, we wanted to know whether using different glue types would have a significant effect on the structural performance of our *E. nitens* mass timber elements. We trialled two different brands of one-component polyurethane (1CPUR) and a resorcinol formaldehyde (RF) in our experiment. We decided against testing phenolic formaldehyde, although it was outlined in our original application, because of the complex infrastructure that would be required for industrial processes to work with an adhesive system that requires heat to set. We also tried but failed to source at least one new generation bio-based structural glue, because one of our current areas of interest is end-of-life uses for mass timber products, and most contemporary adhesives used for structural timber applications limit recyclability. However, despite contacting multiple adhesive providers and contacting international researchers at the University of Gottingen who are researching and developing a special bio-based adhesive for structural uses, we could not source any suitable adhesives for the purposes of this challenge.

Figure 2. Azin mixing RF glue for the sample production at DAF research facility.

Next, we needed to know whether certain industrial processes have a significant effect on the performance of our *E. nitens* mass timber elements. Industrial processes can vary significantly between companies who manufacture engineered wood products, but three key parameters that are universally relevant include press pressure (the amount of force used to push glued timber boards together while the glue sets), pressing time (how long the boards are allowed to cure) and spread rate (the amount of glue that is used). Press pressure may be limited by the type of equipment that a manufacturer has access to and pressing time and spread rate can significantly affect production costs, so optimising these key parameters is useful for anyone planning to manufacture mass timber.

Finally, we needed to know whether surface treatments like planing, face milling, or using a primer would influence the performance of our *E. nitens* mass timber elements. Preparing timber prior to gluing, for example by cleaning or wetting the surface, making it smoother or rougher, can change the way in which adhesives penetrate the timber and limit or enhance their effectiveness (Dugmore et al. 2019, Luedtke et al. 2015).

Given the limited timeframe for the challenge, we streamlined our research and development process into three key tests each designed to answer our specific questions about optimal adhesive types, parameters, and production processes. After brainstorming and designing our prototypes, we enlisted the help of Queensland Department of Agriculture, Forestry and Fisheries (DAF) to manufacture our samples following our methods, but using their specialist equipment. Azin and Jian travelled to DAF to take part in the manufacturing and testing process (see Figures 1 & 2).

Figure 3. Face milling equipment at the DAF research facility, with some of our *E. nitens* sample boards waiting to be milled.

Innovation

To test the structural performance of our prototypes, we primarily based our analytic methods on the requirements outlined in the Australian standards for manufacturing softwood GLT, AS/NZS1328.1 (Standards Australia, 2011), and the European Standard, EN 16351 (British Standards, 2021). It is important to note, that there is no Australian Standard for making or testing CLT, and no standard anywhere in the world for CLT or GLT made from hardwoods. This presents a significant problem for the Australian timber manufacturing industry as well as for those seeking to use engineered wood products made from hardwoods in the built environment.

While preparing our research plan, we consulted with experts at the University of Bern in Switzerland to establish whether we could receive an advance draft copy of a European Standard that they are currently helping to develop for engineered wood products made from hardwoods, but they told us that the draft standard is not even close to completion yet as progress was delayed by the COVID-19 pandemic. However, they did express interest in our research and advised us to use as much precision as possible in the manufacture of our samples, and subject them to a more stringent set of tests than would normally be used to test GLT made from softwoods (i.e. harsher than the tests outlined in AS/NZS1328.1). This influenced our decision to include wet block shear tests into our regime, and to strictly adhere to the specific delamination test requirements by conducting these tests in the specialised facility and equipment at DAF. We also used dry block shear tests on the CLT and GLT samples, as well as bending (MoE) and breaking (MoR) tests on the finger joint samples (Standards Australia, 2006).

Key features and market opportunity

Our product responds to a groundswell of interest in the Australian timber industry in adapting the *Eucalyptus* plantation resource for Australian-based manufacture and production of higher value and more enduring wood products for use in the built environment (Derikvand et al., 2016). Fast growing *Eucalyptus* plantations are widespread throughout Australia and the world. Most of Australia's *Eucalyptus* plantation resource is chipped and exported for pulp and paper production (ABARES, 2018). The economic value that can be returned from a cubic metre of woodchip is market-dependent and is often far less than could potentially be gained by manufacturing and selling plantation material into local construction markets as higher value engineered wood products (ABAREs,

There is an added environmental imperative, because unlike woodchips and paper products, wood products used in the built environment are more enduring and have the capacity to store carbon for decades or even centuries, thus potentially helping to slow down the short-term carbon release cycle (Winchester & Reilly, 2020).

The key features of our product are:

- its specific applicability to an underutilised and undervalued plantation resource (which is abundant all over the world)
- the rigour of our prototyping and testing
- its focus on ease of application and industrial efficiency

Although the adhesives, processing parameters, and surface treatments that we implemented are themselves not new or complicated, the innovation in our product is how we combine these elements to achieve a gluing process that is optimised for a specific hardwood species, and equally, the opportunity this provides to use the Tasmanian *E. nitens* plantation resource more effectively for higher economic returns.

The market for this product would be timber or wood products manufacturers in Australia, but particularly, in Tasmania, who want to use the local Tasmanian plantation resource to make engineered wood products and are looking to streamline their process without reducing the structural efficacy of their product. There is already one company, CLTP / Cusp (2021) making CLT and GLT from fibre-managed plantation *E. nitens* in Tasmania and we could potentially propose this process to them. Another Tasmanian company (Neville Smith Forest Products) has recently greatly increased their production of sawn *E. nitens* boards for appearance applications, while other companies are also increasingly using finger joints and developing smaller scale adhesive-based engineered wood products like stair treads. In the current market, there is great potential for making engineered wood products from plantation *Eucalyptus* material both in Tasmania, Australia, and globally, so our optimised process and parameters are both timely and relevant.

Steps to commercialisation

To commercialise our output, we would first need to undertake further product development and testing to upscale and validate our results. At this point, we are currently at the idea generation stage. This competition has provided us with the ability to screen some of our ideas as well, so next steps would be concept testing and development to create an understanding of the

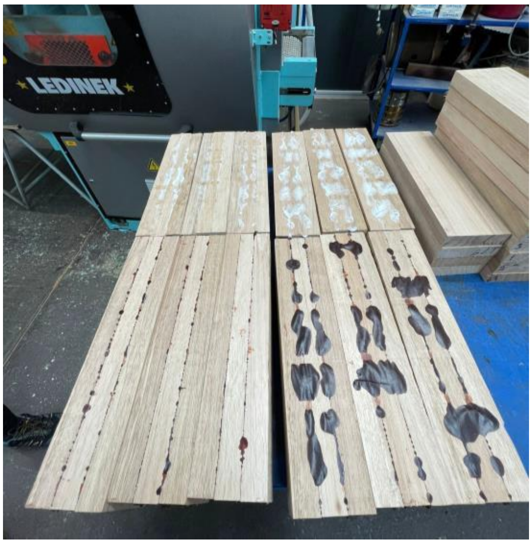


Figure 4. GLT showing different glue types.

Figure 5. CLT cut into blocks for shear test.

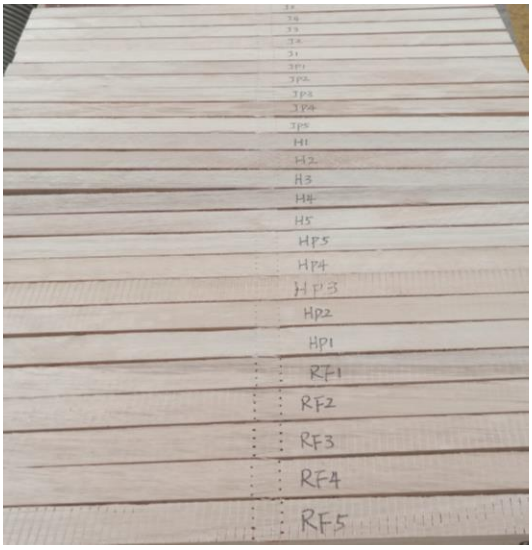


Figure 6. Finger joints with different glues

and surface preparations.

user's perspective, competitor analysis, value proposition, and presenting it to potential customers. There is a potential pathway and support at UTAS for the commercialisation of new products through UTAS Holdings PTY LTD. Alternatively, we could propose to share this work with the Tasmanian timber industry.

Impact and next steps

Both existing and emerging engineered wood products manufacturing processes could potentially change as a result of our findings. For example, existing operators might decide to alter their processing slightly to include face milling or primers as part of the board preparation. This research could also provide invaluable insight for start-up companies, for example regarding purchasing the appropriate equipment to achieve optimal press pressures or including custom-made machinery for specific surface treatments in their production lines.

If we win this challenge, we would like to validate the results of our research with an upscaled trial, seek peer review on our methods by publication in a relevant scientific journal, and follow the steps outlined above towards commercialisation.

The remainder of this document provides an abbreviated report on the materials and methods, results and conclusions from the research project.

Materials and methods (abbreviated)

The timber boards used in this research were sourced from plantation *Eucalyptus nitens (E. nitens)* and dried to a moisture content of 12% before docking and trimming to the dimension 1200mm × 125mm × 25mm (length × width × thickness) to transport to Queensland. The adhesives used were Henkel one component polyurethane, PUR (a), Jowat one component polyurethane, PUR (b) and resourcinol formaldehyde (RF). Throughout this study, cold pressing was used for face and finger joint bonding, and boards were non-edge glued.

For the preparation of CLT specimens, the sawn timbers were further cut into 25mm (thick) × 100mm (width) × 300mm (length). Three lamellas were face bonded using the three different glue types to create a 'parent' billet (see Figure 7). Each CLT billet was made with either different adhesive spread rates, press pressures, or pressing times. After curing, three small block specimens were cut from each parent billets (see Figure 5) and evaluated by delamination according to AS/NZ1328 and block shear tests according to EN 16351 in both dry and wet conditions (note that wet shear tests are not actually required by the standard for GLT from softwood).

Preparation of the GLT billets, followed much the same process as for the CLT billets, however in addition to the use of three glue types, for this test we included different surface treatments prior to gluing as well (see

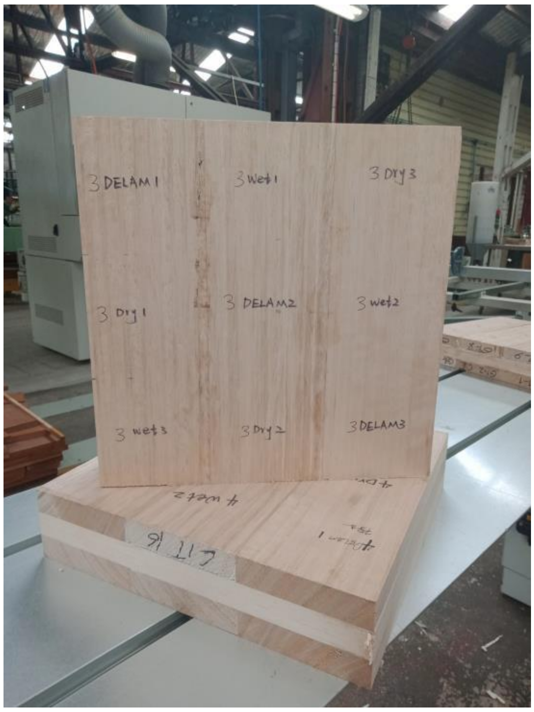


Figure 7. CLT parent billets.

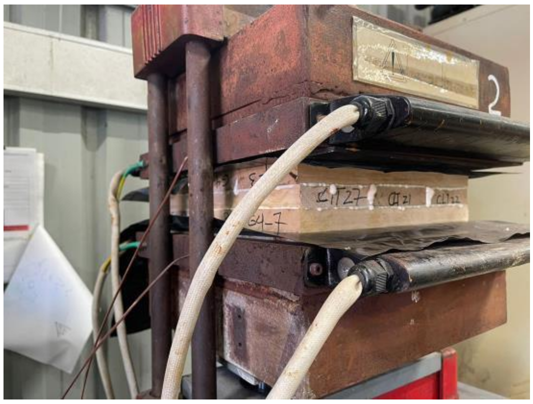


Figure 8. CLT parent billets in the press.

Figure 9. CLT and GLT blocks were block shear tested in both wet and dry condition, using a universal testing machine.

Figure 4). The surface treatments applied in this study were face milling, surface planing, and primer application (see Figure 3). From each GLT billet, three specimens for the delamination test (AS/NZ1328) and six specimens for the block shear test (in both dry and wet conditions, EN 16351) (see Figure 9) were extracted.

Finger joint parent board samples were made from *E. nitens*, using the glue manufacturer's specifications for the parameters for press pressure, spread rate and press time, but with two different finger joint geometries and with one additional treatment type i.e. with primer (see Figure 6). At CSAW, each finger joint parent board was then ripped into three specimens. These samples were tested via a three-point bending test according to AS 5068-2006 (Standards Australia, 2006) and tested either as horizontal finger joints, or vertical finger joints (see Figure 10).

Results and discussion (abbreviated)

The results showing shear strength, percentages of delaminated bond-line, and wood failure of our CLT and GLT specimens were generated via the standard evaluative tests outlined above.

In delamination tests, a separation occurs at the interface between two lamellas when there is an adhesive failure, either within the adhesive or between the layers (see Figure 11). The performance of our CLT panels when subjected to delamination tests revealed that the press pressure significantly influenced bond line failure, whereas glue spread rate and press time did not have a significant effect on the percent of delamination of CLT.

Results from our block shear tests (in both dry and wet condition) (see Figure 12) showed that the mean values of the shear strength under wet condition for all specimen groups were lower than those obtained from dry condition. There was no significant difference in shear strength mean value between the four groups of CLT specimens in dry condition. However, we did learn that press time did not have any significant effect on bonding properties.

Analysis of the results for delamination and block shear tests on our GLT prototype samples indicate that surface milling, and using a primer prior to gluing had a significant effect, enhancing the bonding performance and resulting in no delamination. In contrast, the effect of surface planing was low, and samples showed a higher percentage of delamination than among other treatment groups.

RF adhesive demonstrated good bonding performance. Therefore, it may be concluded that the percent of delamination was not affected by surface planing; however, face milling was found to have significantly affected the delamination percentage values. The highest percent of delamination was related to surface planing using Henkel adhesive.

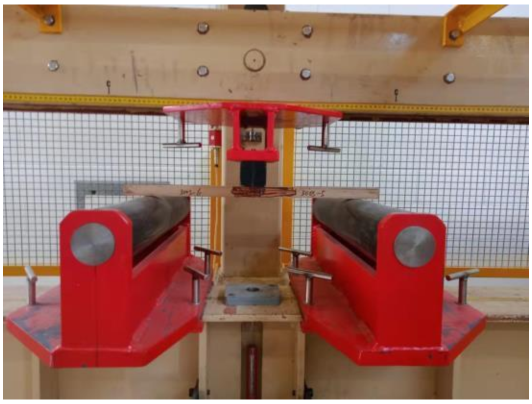


Figure 10. Three point bending test on finger joint samples at CSAW.

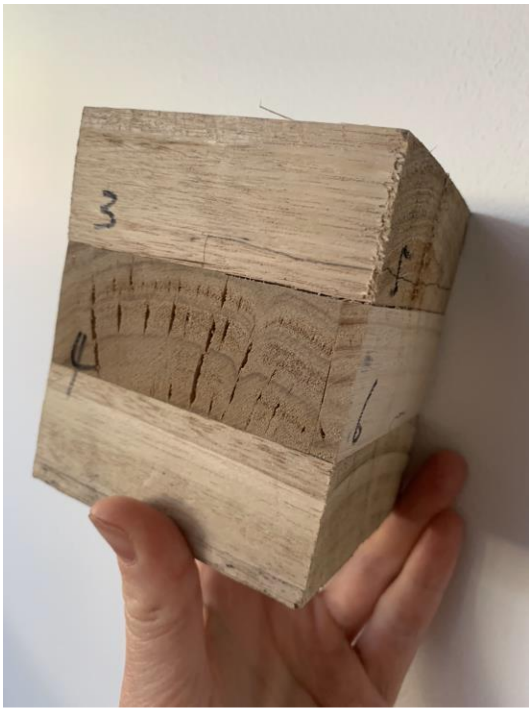


Figure 11. CLT block showing signs of delamination

Figure 12. Samples showing bond line failure after block shear test.

Overall, the results showed that the shear strength of specimens produced with PUR glue (from both Henkel and Jowat suppliers) was increased by using the primer before gluing.

Results from the finger joint tests indicated that vertical finger joints have higher efficiency of MoR, but not MoE. Primer appears to improve the finger joint efficiency of MoE, but not MoR, while geometry affects bonding performance of finger joint significantly. Finger joints with the length of 20mm performed better than those of 10mm (see Figures 13 & 14). Although the mean value and damage mode showed differences in glue types, there was no statistical evidence that they performed differently. Therefore, further research on more samples would help us verify the conclusions obtained in statistical analysis and better understand the performance of different glues.

The finger joint efficiency of MoE varied in different groups. There was no statistical evidence that the mean value tested in a vertical direction was higher than that in the horizontal direction. PUR (b) performed worse in the horizontal experiments than other two types of glue, but in the vertical tests, the efficiency means were similar among the three glue types.

Primer helped PUR adhesives from both manufacturers to improve the finger joint efficiency of MoE in both directions. Meanwhile, the finger joints with the length of 10mm decreased the average efficiency from 0.95 to 0.65 in horizontal direction, and a similar decrease was observed in vertical testing groups (Tukey's test, $P<0.001$).

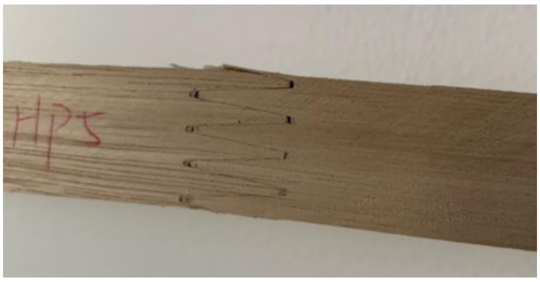


Figure 13. (Top) 10mm finger joint samples after 3 point bending test showing signs of rupture.

Figure 14 (Bottom) 20mm finger joint samples performed better in both MoE and MoR.

Conclusion

This report presents our experimental research on the bonding performance of CLT, GLT and finger joint samples made from plantation *E. nitens*, using different glue types, manufacturing parameters and surface preparation treatments. Based on the results of our CLT assemblies, it can be concluded that press pressure had a significant impact on enhancing the bond performance whereas, press time and adhesive spread rate did not have a remarkable effect on percentages of delamination. It is also worth noting that increasing the glue spread rate did not improve the performance of our prototype mass laminated timber samples from *E. nitens*.

The results from our GLT specimens with three different glue types and different surface treatments indicated that the use of primer when using PUR glue improved the adhesion performance of *E. nitens* mass timber. Furthermore, face milling of the sawn timber prior to gluing was found to positively affect the bonding performance compared to surface planing. In terms of shear bond strength, the highest values were recorded when using primer and PUR adhesive for assemblies. In addition to PUR, resorcinol formaldehyde adhesive demonstrated good bonding performance.

The results from our finger joint assemblies showed that a vertical finger joint has higher efficiency of MoR, but not MoE, while the use of a primer helps improve the overall finger joint efficiency of MoE, but not MoR. Geometry also affects the bonding performance of finger joints, with longer fingers performing significantly better. Although the mean value and damage mode showed differences in glue types, there was no statistical evidence that they performed differently, however this warrants further research.

If we win this challenge, we will use the funds to upscale this trial to validate our results, potentially apply for a patent through UTAS Holdings (and/or work with interested industry partners to do so), and seek peer review through a scientific publication in a relevant journal.

Acknowledgements

First, we would like to acknowledge the excellent support in production and testing from the Queensland Department of Agriculture and Fisheries' Forest Products research unit and thank them for their time and the use of their facilities, in particular, Mr Andrew Outhwaite, Mr Adam Faircloth and Mr Bill Leggate.

We would like to acknowledge the Centre for Sustainable Architecture with Wood, the School of Architecture and Design, and the School of Engineering at the University of Tasmania for their in-kind support. We also want to thank the National University Wood Challenge committee for selecting us to compete in this exciting challenge.

Finally, we would like to thank colleagues at the Bern University in Switzerland, and the University of Gottingen in Germany for their responses to our questions and advice regarding the draft EN Standard for mass timber from hardwoods, and the research and development of bio-based structural glues respectively.

References list

ABARES, 2018, *Australia's State of the Forests Report 2018*, Australian Bureau of Agricultural and Resource Economics and Sciences, Canberra, viewed 6 November 2021, https://www.awe.gov.au/sites/default/files/abares/forestsaustralia/documents/sofr_2018/web%20accessible%20pdfs/SOFR_2018_web.pdf.

British Standards, 2021, "Timber structures – Cross laminated timber – Requirements", EN 16351:2021, Great Britain.

CUSP Building solution, 2021, Australia. Date viewed 5/12/2021. Viewed at: https://cusp.com.au/products/

Derikvand, M., Nolan, G., Jiao, H. & Kotlarewski, N. 2016, 'What to Do with Structurally Low-Grade Wood from Australia's Plantation Eucalyptus; Building Application?', *BioResources*, no. 12, pp. 4 - 7.

Dugmore, M., Nocetti, M., Brunetti, M., Naghizadeh, Z., and Wessels, C. B., 2019, 'Bonding quality of cross-laminated timber: Evaluation of test methods on Eucalyptus grandis panels', *Construction and Building Materials*, vol. 211, pp. 217 – 227.

Ettelaei, A.; Taoum, A.; Nolan, G. Rolling shear properties of cross-laminated timber made of fibre- managed plantation 404 eucalyptus under short-span bending. Wood Material Science & Engineering 2021, 1–8. 405 https://doi.org/10.1080/17480272.2021.1942201

ISO 12580, 2007, "Timber structures —Glued laminated timber —Methods of test for glue-line delamination," International Organization for Standardization, Geneva, Switzerland.

Luedtke, J et al. 2015, "1C-PUR-bonded hardwoods for engineered wood products: influence of selected processing parameters," *European Journal of Wood and Wood Products*, vol. 73, no. 2, pp. 167–178, viewed 11 November 2019, http://link.springer.com/10.1007/s00107-014-0875-8

Standards Australia, 2011, "Glued laminated structural timber. Part 1: Performance requirements and minimum production requirements", AS/NZS 1328.1:1998 (Incorporating AmendmentNo.1), Sydney, Australia.

Standards Australia, 2006, "Timber - Finger joints in structural products - Production requirements", AS 5068-2006, Sydney, Australia.

Winchester, N. & Reilly, J. M. 2020, 'The economic and emissions benefits of engineered wood products *in a low-carbon future', Energy Economics, DOI: 10.1016/j.eneco.2019.104596.*

Link to 2-minute video

https://drive.google.com/file/d/1ULZcWOznNTvoXy8JXAyfTjQ-8sOSwBxe/view?usp=sharing

Bern University of Applied Sciences
Institute for Materials and Wood Technology IWH

Martin Lehmann

Solothurnstrasse 102
Post-Case 6096
2500 Biel 6

Phone 032 344 03 21

martin.lehmann@bfh.ch
www.bfh.ch/ahb

BFH-AHB | Post Case 6096 | 2500 Biel 6

NIFPI 80 Lamination project

11 May 2020

Why are delamination test needed to verify the quality of adhesively bonded hardwoods?

Standards

The current standards (in Europa, USA and Australia) considering the structural bonding and especially the ones defining the quality control of glulam and cross laminated timber are developed for softwoods and therefore if one likes to apply them for hardwoods some adoptions are needed. Currently no standard for the quality control of structural bonds in hardwoods is published in Europe. However, an European standard considering the production of hardwood glulam is developed and in Switzerland productions guidelines for hardwood glulam will be published soon. Two different methods for the quality control will be considered in this future standards: Delamination test of glue lines will be the recommended method, however for some species this method is not applicable (e.g. tropic hardwood with extreme high density or stabilized woods) therefore in the European Standard a method involving soaking in hot water and wet shear test will be considered. Dry shear tests as for softwoods will not be allowed for the quality control of structural bonded hardwood in European standards and the Swiss guidelines.

Scientific Publications

Serval investigations [1-8] showed that adhesives for load-bearing timber structures can show an excellent performance in dry shear tests[1] in combination with catastrophic behaviour in the determination of resistance to delamination along EN 302-2. This is not only valid for PUR but for most adhesive types. Knorz et al. [4] investigated the bonding performance of European ash (*Fraxinus Excelsior*) and showed that all adhesives showed an excellent performance at the dry shear test. PUR for example had a shear resistance of 13.2 MPa in combination with an average wood failure of 63% tested along the EN 14080:2013 Appendix D. However, the average delamination for the same series was above 80% and some specimens showed even complete delamination. Similar results were obtained by Ammann et al [1]. Schmidt et al. [8] published similar results for European Beech (*Fagus Sylvatica*). Clerc et al. [2] and Lehmann et al. [6] showed that the application of a primer allows to

[1] Two different European standards describe methods for dry shear tests: EN 14080:2013 Appendix D "Shear test of glue lines" (formerly EN 392). EN 302-1:2013 "Adhesives for load-bearing timber structures - Test methods - Part 1: Determination of longitudinal tensile shear strength" the treatment A1 is a dry shear test and A4 is a wet shear test.

Affiliated school:
Higher Technical School of Wood Biel

reduce the delamination to an acceptable level for European ash and beech (below 5% in tests along EN 302-2:2013).

Conclusions
The Publications clearly show that a good performance in a dry shear test is not enough to verify the quality of a bond of hardwood glulam or CLT. However, delamination tests proofed to be an adequate method for the quality control furthermore industrial producers experienced a good correlation between the laboratory tests and the performance during service life. The publications also show that PUR-adhesives only show a good performance in combination with European hardwood if a primer is used. However, for low density hardwood it is may also possible to reach acceptable performance without primer. Therefore, it is very important to start as soon as possible basic investigations about the bonding performance of PUR using fibre-managed plantation eucalyptus nitens to define if a primer needs to be applied or not.

List of Publications

1. Ammann, S., S. Schlegel, M. Beyer, et al., *Quality assessment of glued ash wood for construction engineering.* European Journal of Wood and Wood Products, 2016. **74**(1): p. 67-74.
2. Clerc, G., M. Lehmann, C. Lehringer, et al. *Improvement of ash (Fraxinus Excelsior l.) bonding quality with one component polyurethane adhesive and a primer for glued laminated timber*. in *WCTE 2018*. 2018. Seoul (Republic of Korea).
3. Ehrhart, T., R. Steiger, M. Lehmann, et al. *European beech (Fagus sylvatica L.) glued laminated timber: Lamination strength grading, production and mechanical properties*. in *ISCHP19*. 2019. Delft: TU Delft.
4. Knorz, M., M. Schmidt, S. Torno, et al., *Structural bonding of ash (Fraxinus excelsior L.): resistance to delamination and performance in shearing tests.* European Journal of Wood and Wood Products, 2014. **72**(3): p. 297-309.
5. Knorz, M.H., *Investigation of structurally bonded ash (Fraxinus Excelsior L.) as influenced by adhesive type and moisture*, 2015, Technische Universität München: München.
6. Lehmann, M., G. Clerc, C. Lehringer, et al. *Investigation of the Bond Quality and the Finger Joint Strength of Beech Glulam*. in *WCTE 2018*. 2018. Seoul (Rep. of Korea).
7. Lehmann, M., S. Schlegel, S. Ammann, et al. *Investigation of the Bond Quality of Semi Industrially Produced Ash Glulam*. in *WCTE 2016*. 2016. Vienna (Austria).
8. Schmidt, M., P. Glos, and G. Wegener, *Verklebung von Buchenholz für tragende Holzbauteile.* European Journal of Wood and Wood Products, 2010. **68**: p. 43-57.

Kind regards

Bern University of Applied Sciences
Institute for Materials and Wood Technology IWH

Martin Lehmann

Affiliated school:
Higher Technical School of Wood Biel

1. Starting point

The projects aim is to develop the grading, jointing and gluing expertise necessary for the production of structurally reliable glue-laminated elements using boards from a fibre-managed plantation hardwood resource. In the project, the feedstock recovered from unthinned and unpruned Eucalyptus nitens will be utilised for producing and testing of glulam samples.

In order to do so, two preliminary tests were selected to be carried out; tension tests on finger joints, and delamination of glulam beams.

The first step of the project was to assess the boards (L=3m, w≈125mm, t≈25mm; for the time being only remaining boards from the Dubai project with unknown provenance are used), and specify the possibility and position of the required samples for making new finger joints and glulam beams. Each board was given a name starting with E1 and going up to E85.

2. Finger joints

2.1 Requirements and limitations for new finger joint production and testing

For the new finger joints a total length of at least 1 meter was required by the companies for each of the two connecting members (each side of the finger joint). This is the lower limit that the finger joint machine can handle. Also, for the transportation and workability, a maximum board length of 1.2 m was decided. Based on the EN 14080 & EN 408 standards requirements for the allowable position of knots in the board, and the configuration of the tensile testing machine the tensile test pieces were specified. Initially, the position of the new finger joint was chosen so that the existing finger joints and major knots in the boards will be at least 40 cm and 35 cm away from the new finger joint respectively; however, two additional classes of finger joints were added which will be covered in section 2.2. The test sample for the tensile test should be at least 120 cm; 60 cm on each side of the new finger joint, 20cm clear and 40cm clamped. The sample Is then placed in two 40 cm clamps on each side, leaving a total of 40 cm in the middle unclamped.

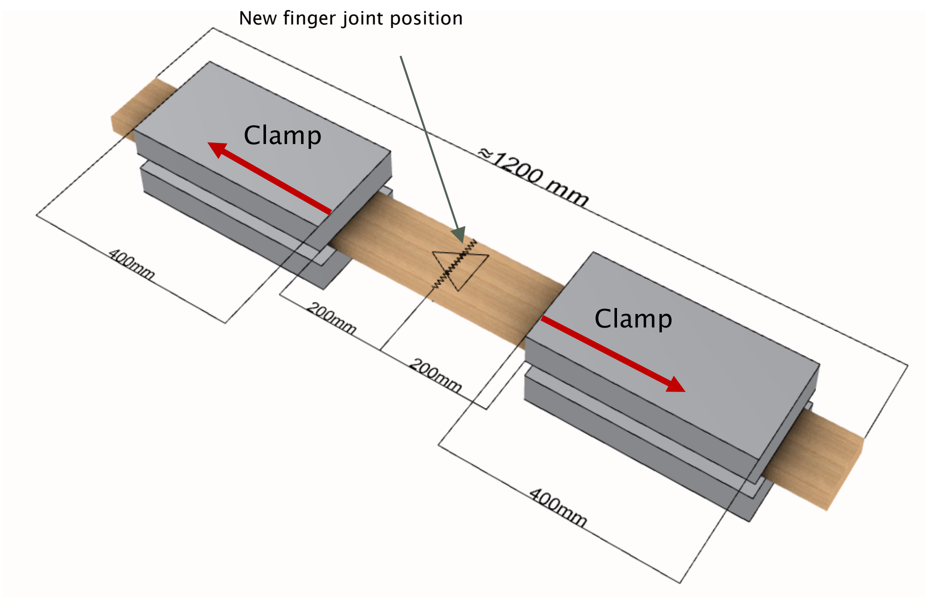


Figure..1: simplified setup of the tension test with the position of the new finger joint and the clamps.

2.2 Assessment of the boards for new finger joint production

Each board was assessed carefully to insure the maximum number of finger joint connecting elements were taken out. This meant that the spacing required for the testing and production of the new finger joints had to be marked where possible. In many cases each board had only the possibility of giving one side of a new finger joint, whereas some boards had 2, or even 3 elements for new finger joints in them. For each portion of the board suitable for one connecting element of a new finger joint a new name was given; e.g. E5_F1. The first part shows to which board it belongs, and the second part, the number of the finger joint element.

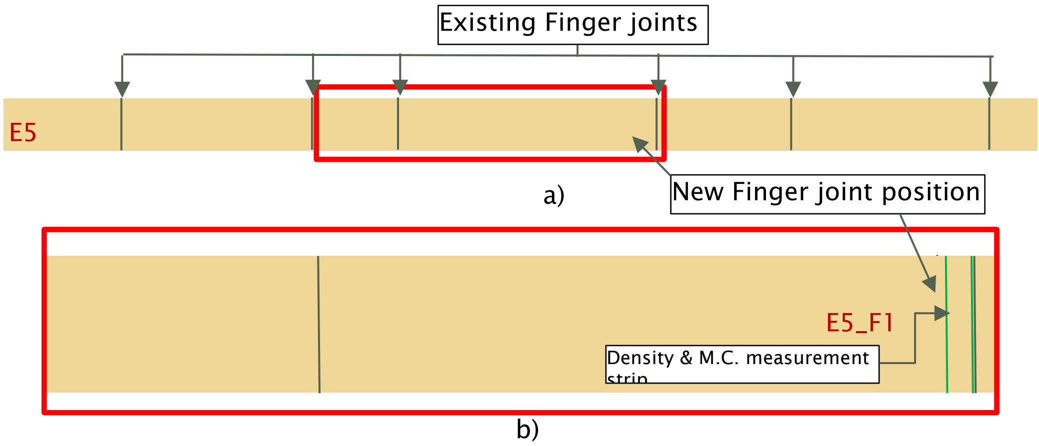


Figure. 2: a) The original length (=3m) of the received board, the position of the existing finger joints, and the possible position of one side of a new finger joint. b) The part (min 1 m) of the original board suitable for one side of a finger joint and the position of the density and M.C. measurement strip.

However, after going through all the boards, the number of possible samples for new finger joints did not reach 30 in total. Thereafter another assessment was done on the boards, this time the position of every existing finger joint, side knot, middle knot, crack, and drying collapse was recorded and the samples were categorized into 3 classes.

2.2.1 Class 1A

Class 1A were the samples which had the closest existing finger joint further that 40 cm from the position of the new finger joint, the closest considerable knot further than 35 cm from the position of the new finger joint, and the first 20 cm free of any defects (very minor defects were overlooked).

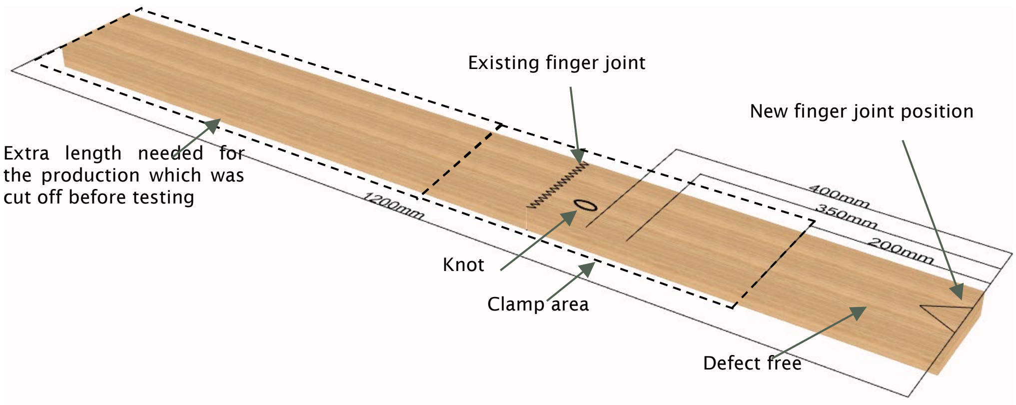


Figure.3: simplified representation of class 1A

2.2.2 Class 1B

Class 1B were the samples which had the closest existing finger joint at least 40 cm from the position of the new finger joint, but the position of knots no longer had the limit of at least 35 cm, and the first 20 cm could have minor defects or knots.

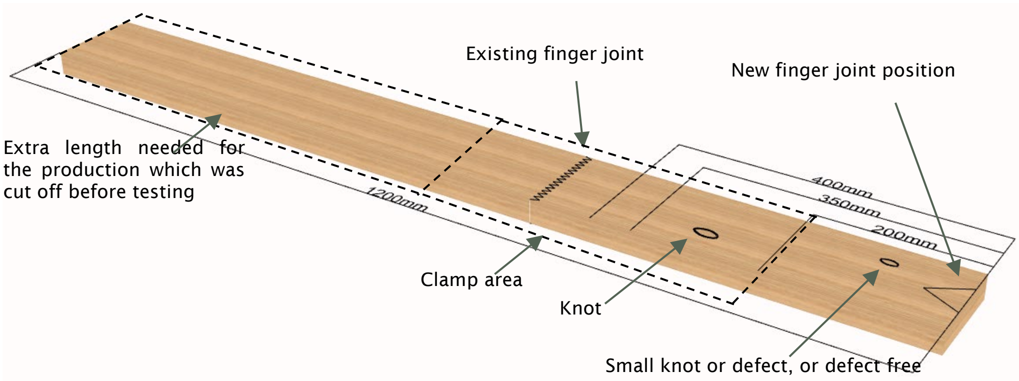


Figure.4: simplified representation of class 1B

2.2.3 Class 2A

Class 2A were the samples which had the closest existing finger joint less than 40 cm from the position of the new finger joint, and may or may not have minor knots and defects.

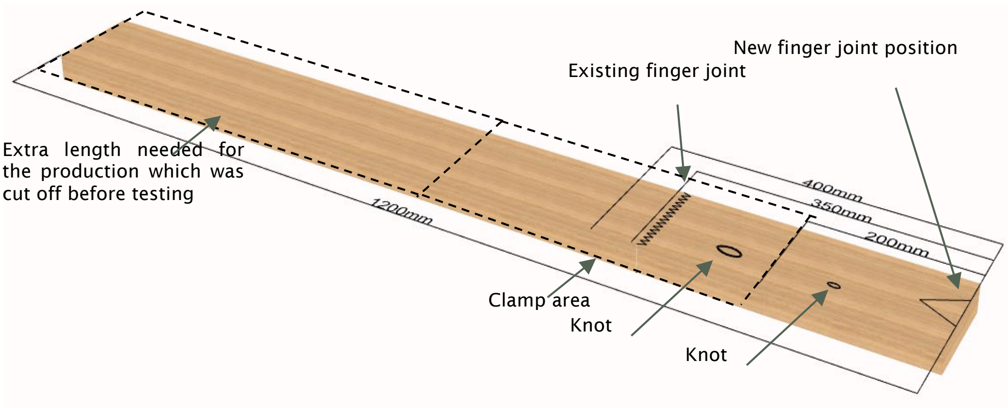


Figure.5: simplified representation of class 2A

The existing knots in the adjacent 40 cm to the place of the new finger joints were categorized into 3 sizes and 2 positions; small, medium, and big, Side, and middle. This was done so that the two connecting members of one finger joint would be paired based on their visual defects to have symmetrical load distribution in the two sides of the finger joint when being tested. When recording the knots, the category was stated for example as "MSN", meaning "Medium Side kNot". For finger joints, cracks, and drying collapse, the short terms "F", "CR", and "CO" was stated respectively.

Element	Finger joint	defect in first 20cm @	type of defect	additional defect	defect in second 20cm @	type of defect	additional defect	class
E41	3	0	-		9	F		2A
E19	1	0	-		9	SMN	CR	2A
E47	2	0	-		10	F		2A
E69	2	0	-		11	F		2A
E58	1	0	CR		11	F	6SMN	2A
E42	1	0	-		12	F	Resin Pocket	2A

Table 1: Input of existing defects for each assessed board in the respective class

2.3 Assessment of the density and M.C.

Additionally, for determining the density, a 25 mm test piece was marked at the start of each member to be cut off, figure 2.b. The size of the density sample is based on the requirements of the EN 13183-1. From the total number of samples, 11 were selected for the determination of the moisture content. The 11 samples were selected so to represent the range of the density of the boards which varied from 466 kg/m^3 to 717 kg/m^3. After drying in the oven for 24 hours, the samples were weighed again. After nearly 3 hours, the weight difference to the prior weight was not greater that 0.1% and the moisture content was calculated. The average moisture content was 11%. The density and M.C. strips were scanned to have their growth rigs documented.

Each recorded element to receive new finger joints was put into MS Excel along with the specifications of the different kind of defects and their distance to the new finger joint. The initial pairing of the elements was done within each of the classes-1A, 1B, and 2A- so that the two elements joined by the new finger joint would have the most possible symmetry of defects, including knots, cracks, drying collapse, and etc.

After the determination of the density of each member, it was formulated to find the density of each connecting member of the new finger joint; specifying which density class is joined with which density class. Three density classes were specified based on the normal distribution of the densities, and the probability of 33% for low (466-556 kg/m^3), average (556-609 kg/m^3), and high (609-717 kg/m^3).

Sample name	connecting piece	New finger joint name	joining members	density left	density right	density class left	density class right	Joint class
E41_F3	E42_F2	NC1	E41_F3_E42_F2	671	525	high	low	3
E19_F1	E71_F1	NC2	E19_F1_E71_F1	532	659	low	high	3
E47_F2	E69_F2	NC3	E47_F2_E69_F2	587	486	avg	low	1
E69_F2	E47_F2							
E58_F1	E42_F1	NC4	E58_F1_E42_F1	621	565	high	avg	4
E42_F1	E58_F1							

Table 2: Pairing of the members for the production of new finger joints and the assignment of their density classes

Connecting densities	Range of connecting densities	finger joint density class	# of class 1A FJs	# of class 1B FJs	# of class 2A FJs	Total FJs in density class
low-low	(ρ<556kg/m3)-(ρ<556kg/m3)	0	1	4	2	7
avg-low	(609kg/m3>ρ>556kg/m3)-(ρ<556kg/m3)	1	6	5	2	13
avg-avg	(609kg/m3>ρ>556kg/m3)-(609kg/m3>ρ>556kg/m3)	2	3	4	1	8
high-low	(ρ>609kg/m3)-(ρ<556kg/m3)	3	4	7	4	15
high-avg	(ρ>609kg/m3)-(609kg/m3>ρ>556kg/m3)	4	5	6	2	13
high-high	(ρ>609kg/m3)-(ρ>609kg/m3)	6	0	4	1	5

Table 3: Density and joint classes with number of FJs belonging to each.

Each joint class will be divided into 3 groups to be taken to the companies. One group for Fagus (F), one group for the softwood process in n'H (S), and the last group for the hardwood process in n'H (H). The goal will be to have 21 finger joints per group.

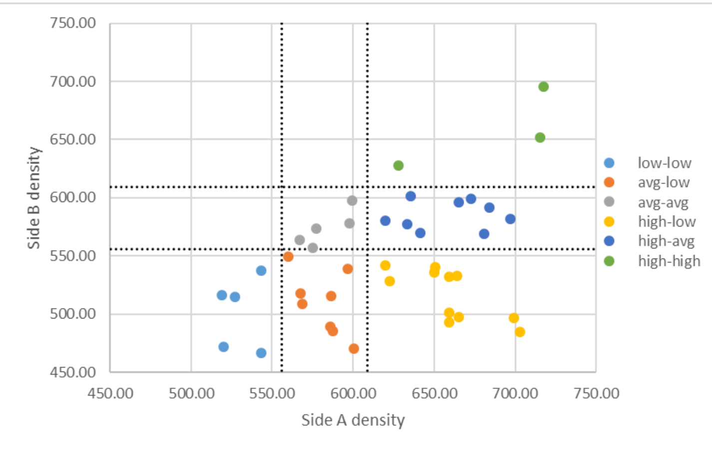


Figure 6: Density class of each new finger joint made at n'H shown based on the density of the two connecting members. The dashed lines represent the lower and upper limit of the average density (556-609 kg/m^3).

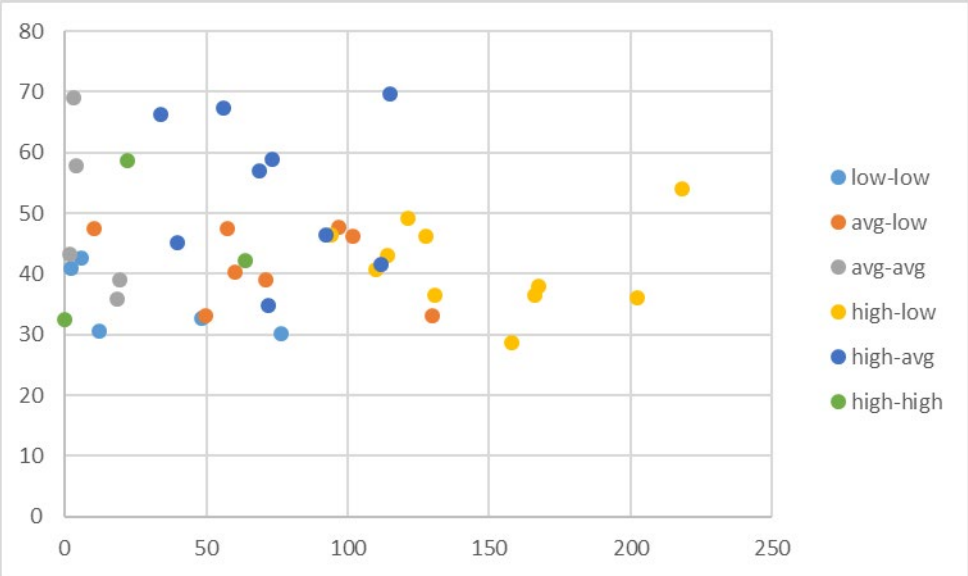


Figure 8 : Absolute Density difference of the connecting members vs. strength of finger joint:

Plotting all acquired values from the tension test of the new finger joints, against the absolute density difference (of two members of one new finger joint), does not show significant correlation between the density difference and strength. One takeaway from figure 7 is that in the presence of a member with low density (<556 kg/m³) the deviation in the finger joint strength has a smaller range than the finger joints that do not have a member with low density.

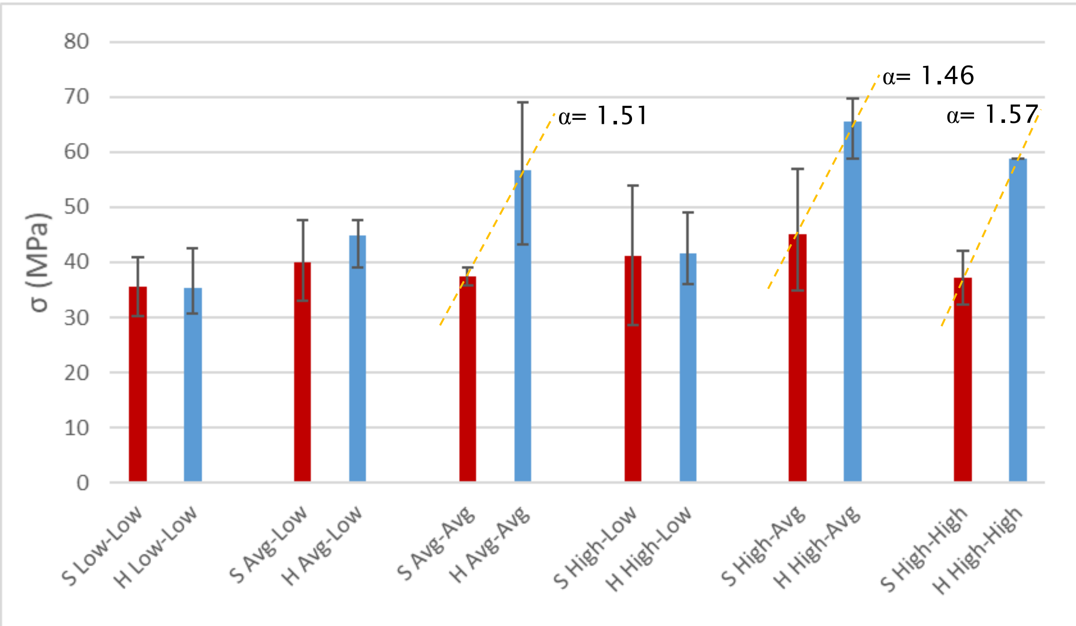


Figure 7: Average strength by class and process

The previous discussion is backed up when illustrating the average, max, and min strength of the finger joints by their density class and the process of making the finger joint (softwood process vs. hardwood process). It can be clearly seen that in the absence of low-density members, the average strength is nearly increased by 50% when making the finger joints using the hardwood process. However, this difference in strength when applying the different process is nearly nullified when at least one of the connecting members is of low density. It can be discussed that this pattern is due to the fact that the hardwood process was designed and adapted for hardwood species which have relatively high densities; whereas the low-density class has a range of density between 460 and 556 kg/m³.

FJ density class	New finger joint name	joining members	production company	FJ density class	New finger joint name	joining members	production company	FJ density class	New finger joint name	joining members	production company
0	NA15	E13_F1_E73_F1	F	0	NB12	E53_F1_E84_F2	H	0	NB27	E66_F1_E05_F2	S
0	NB14	E64_F3_E33_F2	F	0	NB13	E25_F2_E37_F2	H	0	NC11	E10_F1_E59_F1	S
1	NA19	E76_F2_E54_F2	F	0	NC8	E03_F1_E08_F1	H	1	NA13	E48_F2_E47_F1	S
1	NA3	E84_F1_E68_F1	F	1	NA16	E31_F1_E02_F2	H	1	NA18	E26_F1_E78_F2	S
1	NB23	E63_F1_E39_F1	F	1	NA9	E16_F2_E22_F1	H	1	NB6	E11_F1_E26_F3	S
1	NB25	E61_F2_E81_F2	F	1	NB5	E62_F2_E56_F2	H	1	NC3	E47_F2_E69_F2	S
1	NB3	E05_F1_E40_F1	F	1	NC10	E08_F2_E67_F1	H	2	NA17	E53_F2_E69_F1	S
2	NA2	E25_F1_E85_F1	F	2	NA8	E16_F1_E20_F1	H	2	NB19	E24_F1_E06_F2	S
2	NB10	E79_F1_E60_F1	F	2	NB15	E52_F1_E17_F1	H	3	NA12	E49_F1_E48_F1	S
2	NC7	E76_F1_E56_F1	F	2	NB24	E23_F1_E04_F1	H	3	NA14	E47_F3_E44_F1	S
3	NA7	E24_F2_E44_F2	F	3	NA10	E22_F2_E79_F2	H	3	NB4	E13_F2_E59_F2	S
3	NB2	E63_F2_E44_F3	F	3	NB1	E85_F2_E81_F1	H	3	NB8	E82_F1_E41_F1	S
3	NB29	E26_F2_E64_F2	F	3	NB11	E09_F1_E74_F1	H	3	NC12	E49_F2_E71_F2	S
3	NC1	E41_F3_E42_F2	F	3	NB30	E31_F3_E27_F1	H	4	NA5	E64_F1_E32_F1	S
3	NC6	E41_F2_E75_F2	F	3	NC2	E19_F1_E71_F1	H	4	NA6	E31_F2_E20_F2	S
4	NA1	E02_F1_E14_F1	F	4	NA11	E70_F1_E57_F1	H	4	NB20	E51_F1_E50_F1	S
4	NB16	E40_F2_E75_F1	F	4	NA4	E83_F1_E57_F2	H	4	NB31	E62_F1_E70_F2	S
4	NB22	E80_F1_E10_F2	F	4	NB17	E15_F1_E09_F2	H	4	NC9	E29_F1_E29_F2	S
4	NC4	E58_F1_E42_F1	F	4	NB26	E07_F1_E78_F1	H	6	NB21	E33_F1_E37_F1	S
6	NB9	E33_F3_E43_F1	F	6	NB18	E32_F2_E28_F1	H	6	NB28	E77_F1_E77_F2	S
6	NC5	E58_F2_E61_F1	F		NB32	E35_F1_E11_F2	H		NB7	E52_F2_E06_F1	S

Table 4: List of all new FJs to be produced along with the joining members and the production process, F for Fagus, H for the hardwood process at n'H, and S for the softwood process at n'H.

3. Glulam Beam & delamination test

. Delamination tests proofed to be an adequate method for quality control and to determine suitable adhesives with and without primer in the gluing process. It is important to investigate the bonding performance of PUR using fibre-managed plantation E. nitens and to perform delamination test to proof that bonding is adequate. For the species in question it must be shown if a pre-treatment with primer is required or not. To do so, the first delamination test is done without the use of primer. In this way if the delamination exceeds the limit, the use of primer could be considered to bring the delamination below the limit requested by the standard.

3.1 Requirements and limitations for glulam production and delamination test

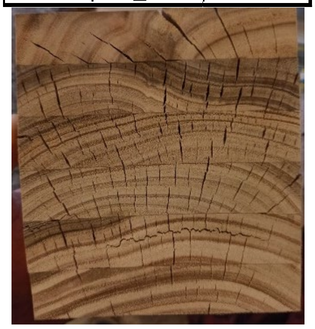
The delamination test was done based on the EN 302-2 standard. EN 302-2 requests lamellas with a thickness of 30 mm this was not possible to reach as the lamellas from the Dubai project had 25 mm only. Based on the standard, for each glulam beam, six lamellas with tangential cuts is needed. The minimum required lamella length is 500 mm. From each produced glulam beam a maximum number of four 75mm samples were needed. Therefore, in the assessment of the boards (L=3m, w≈125mm, t≈25mm; for the time being only remaining boards from the Dubai project with unknown provenance are used), the boards having a clear surface (finger joint, knot, and defect free) in at least 300mm of length were marked with an extra 150mm on each side. This would yield a 600 mm board that will be used to build the glulam beam. The naming of the selected elements is done similar to the one explained in the finger joint section, with the replacement of the letter “F” with “D”; e.g. E80_D1.

3.2 Glulam production

A total of 30 boards with a length of 600mm were cut out from the 3m boards, and stored in the climate room (M.C. 65%, temp 20°C) for a period of 2 weeks. Then 12 of the boards with the highest density were planed and two glulam beams were produced (180g/mm^2 of one component PUR glue) in the Energy lab at the BFH in Biel. The density range of the first glulam (G1) is from 617kg/m^3 to 706kg/m^3 with the average of 654kg/m^3. The density range of the second glulam (G2) is from 568kg/m^3 to 609kg/m^3 with the average of 586kg/m^3. The two glulam beams were then climatized again for two weeks (a minimum of 7 days is required by the standard) before the specimens were prepared.

Glulam name	Element name	Density kg/m3
G1	E80_D1	676
	E2_D1	665
	E15_D1	630
	E17_D1	628
	E17_D2	617
	E36_D1	706

Glulam name	Element name	Density kg/m3
G2	E38_D1	606
	E18_D2	608
	E1_D2	590
	E72_D2	578
	E1_D1	568
	E45_D1	568



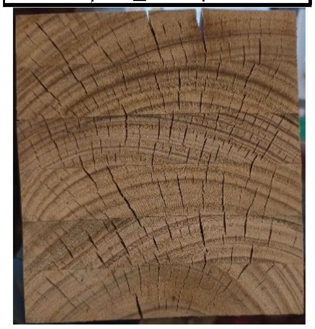


Figure 9: List of the two produced glulam beams comprising lamellas along with their densities and their cross section after first drying.

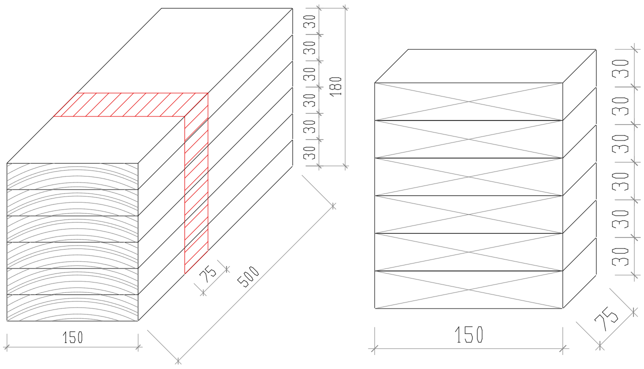


Figure 10 : Laminated beam and specimen (red and right) as requested by EN 302-2

3.3 Delamination test

The delamination test comprises of 3 set of cycles. Each cycle includes the water absorption phase and drying phase. The water absorption is done in an autoclave, figure 7.a. The drying is done in the dryer, figure 7.b, with controlled humidity and airflow speed.

(a) (b)

Figure 11 : Devices used in delamination test; a) Autoclave, b) Air dryer with controlled humidity and airflow speed.

3.3.1 Water absorption according to EN 302-2:
Reduce the pressure in the autoclave to (25 ± 5) kPa absolute and maintain this pressure for 15 min. Release the vacuum and apply a pressure of (600 ± 25) kPa absolute for 1 h. The test pieces being still completely submerged, repeat this pressure-vacuum treatment once more to obtain a period of impregnation over two cycles totalling approximately 2 h 30 min.

However, after completing the first water absorption phase it was noticed that the specimens did not absorb enough water, 29% for G1 and 46% for G2. There was the probability that water did not reach the centre of the 75mm specimen, and thus would not be imposed to enough internal tension to reach proper delamination results. To compare the water absorption to other hardwoods, 6 beech glulam specimens were included in the next cycles; beech exhibited 72% of water absorption in the first water absorption phase.

Until the third cycle, the water absorption of the Eucalyptus specimens increased to 36% for G1, and 55% for G2, whereas the water absorption of the beech specimens reduced to 60%, but the total weight after impregnation stayed more or less equal for beech. Nevertheless, the water absorption of the Eucalyptus specimens did not reach a satisfactory value to ensure correct results from the delamination test.

3.3.2 Drying according to EN 302-2:
Dry the test pieces for (20 ± 2) h in an oven … at a temperature of (65 ± 3) ˚C and relative humidity of (12.5 ± 2.5) %. During drying, place the specimens at least 50 mm apart, with the surfaces across

the grain parallel to the airflow. After a drying period of 18 h, check the mass of the test pieces on a balance to the nearest gram. It should be estimated that the impregnation-drying cycle of any test piece is finished only when the mass of the test piece is between 102% and 108% of the original mass (m_0). If the mass of a test specimen given exceeds its original mass (m_0) by more than 8% after 18 hours of drying, place the test piece again in the drying tunnel and subject it again to the same drying conditions. Take out the test piece and reweigh its mass after 1 h. Repeat this procedure until the mass of the test piece is within the required range. All specimens must be dried in a delay of 22 h. Some hardwood species may require longer drying time, but the drying period should not exceed 30 hours.

Since the drying time of Eucalyptus specimens were unknown, they were weighed before the 18 hours specified in the standard; 10 hours after the start of the drying process the mass of the specimens were in the required limit of 102% to 108% of the initial mass. For the Beech specimens, the initial drying time was 18.5 hours. Towards the end of the 3rd cycle, the drying time of the Eucalyptus specimens increased to 14 hours, and the Beech specimens decreased to 17 hours.

#	Initial Mass	Mass 1. after Autoclave	water absorbtion	Mass 1. after Drying	Duration 1. Drying	mass befor autoclave 2	Mass 2. after Autoclave	water absorbtion	Mass 2. after Drying	Duration 2. Drying	mass befor autoclave 3	Mass 3. after Autoclave	water absorbtion	Mass 3. after Drying	Duration 3. Drying	Mass 102%	Mass 108%
Nom	[g]	[g]	%	[g]	[h]		[g]	%	[g]	[h]		[g]	%	[g]	[h]	[g]	[g]
G1-1	818.35	1051.7	28.51	843.8	09:18:00	_	1126.43	33.49	861.05	13:30:00	837.76	1141.95	36.31	862.9	13:00:00	835	884
G1-2	818.9	1062.6	29.76	835.3	13:30:00	825.99	1115.10	35.00	857	13:00:00	854.00	1157.55	35.54	865.4	13:30:00	835	884
G2-1	708.15	1032.4	45.79	760.55	09:18:00	_	1148.90	51.06	747.5	18:30:00	731.00	1144.55	56.57	764.8	15:50:00	722	765
G2-2	707.65	1037	46.54	747.75	13:30:00	722.34	1114.90	54.35	758.25	15:50:00	754.05	1161.40	54.02	761.7	17:00:00	722	764
X1	1455.15	2549.2	75.18	1547.2	18:30:00	1494.85	2538.90	69.84	1562.3	15:50:00	1553.55	2540.20	63.51	1539.9	17:00:00	1484	1572
X2	1520.15	2609.6	71.67	1633.5	18:30:00	1580.35	2595.70	64.25	1633.8	15:50:00	1625.50	2592.15	59.47	1612.2	17:00:00	1551	1642
X3	1460.5	2551.1	74.67	1554.65	18:30:00	1534.05	2540.79	65.63	1569.1	17:50:00	1562.00	2542.35	62.76	1576.25	17:00:00	1490	1577
X4	1539.05	2557.25	66.16	1639.95	18:30:00	1594.45	2553.90	60.17	1640.85	17:50:00	1632.90	2556.60	56.57	1648	17:00:00	1570	1662
X5	1495.75	2582.9	72.68	1609.7	18:45:00	1552.60	2586.70	66.60	1613.1	17:50:00	1603.40	2586.30	61.30	1615.05	17:00:00	1526	1615
X6	1497.35	2585.4	72.67	1609.2	18:30:00	1578.55	2571.50	62.90	1616.7	18:20:00	1607.95	2572.30	59.97	1604	18:40:00	1527	1617

Table 5 : recorded data during the delamination test regarding the water absorption and drying. “G” is for the Eucalyptus specimens and “X” is for the Beech specimens.

Bending Testing of Tas Oak Glulam to AS/NZS4063 Characterization of structural timber

Authors: Dr Marcus Jungtae Noh
Dr Assaad Taoum

Bending Testing of Tas Oak Glulam to AS/NZS4063
Characterization of structural timber

UNIVERSITY of TASMANIA

centre for sustainable architecture with wood
CSAW

NATIONAL INSTITUTE FOR FOREST PRODUCTS INNOVATION

Executive summary

This report outlines the glulam production work using Tasoak sawn boards in the framework of the NIFPI project *Developing laminated structural elements from fibre-managed plantation hardwood*. The aim of the structural glued-laminated timber (glulam) production trial is to investigate bending strength (MoR) and Modulus of elasticity in bending (MoE). In this trial, five three-ply glulam elements (1815 x 100 x 70 mm^3) were produced and tested. The samples have Vertical finger joint. Finger length and pitch is approximately 19 mm and 4 mm, respectively.

Methodology

The glulam elements were tested in accordance with the test methods in AS/NZS 4063.1:2010 to determine bending strength, apparent modulus of elasticity (stiffness) and shear strength. Bending strength: Effective span: 1800 mm. Two load point at: 600 mm. See Figures 1 and 2.

MOE and MOR testing was on a Cailbre Equipment four point bending machine certified by AusCal. The CSAW Calibre “testing machine enables timber to be tested for bending stiffness and strength in accordance with AS/NZS4063”. Elements were loaded in the major axis to failure. Load and deflection data were captured in accordance with AS/NZS 4063.1:2010 through a customised Labview interface. Data processing was carried out in Excel. Elements were loaded to failure in approximately 2 to 5 minutes, in accordance to AS/NZS 4063.

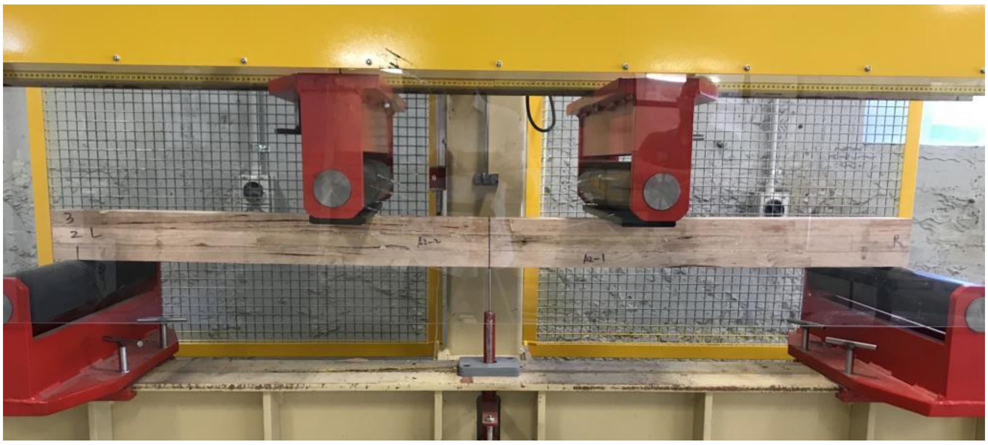
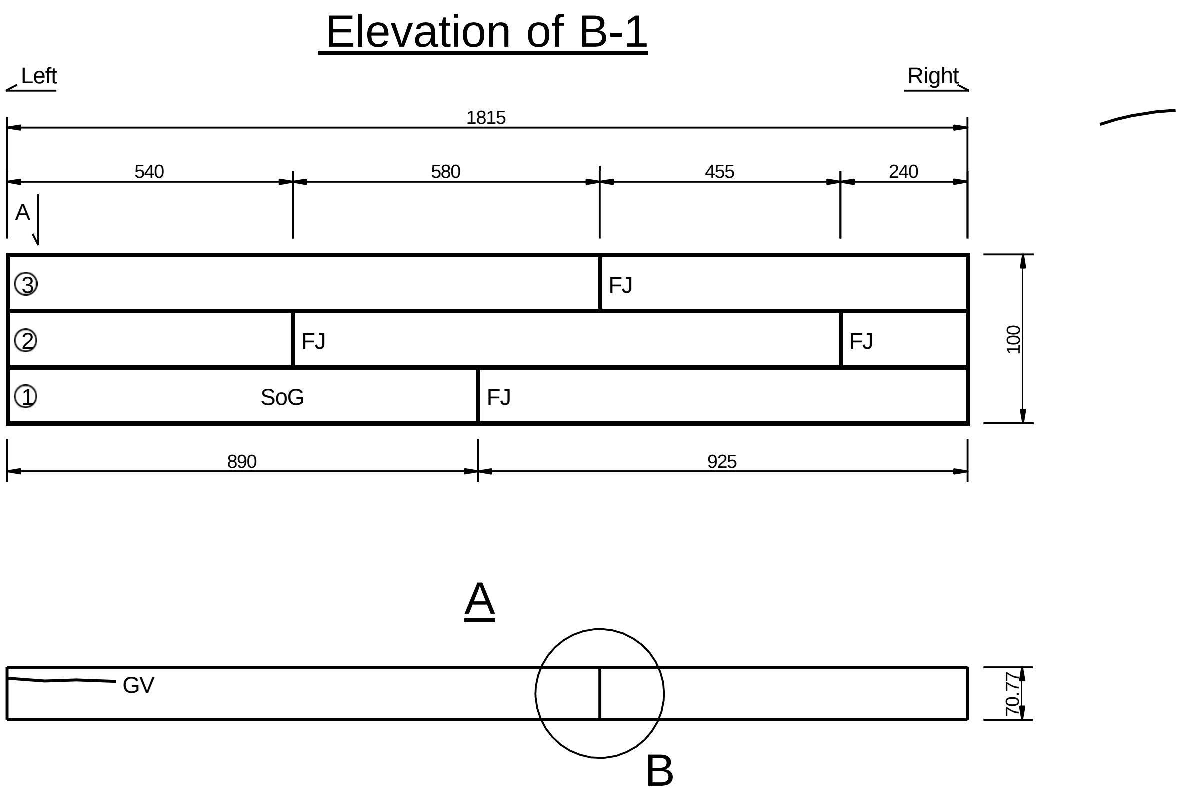
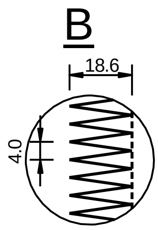


Figure 1: Four-point bending test setup (Sample ref. A-1)





Note:

1. Unit: mm.
2. FJ - finger joint; SoG - slope of grain; GV - gum vein.
3. Bcak sawn boards.

Figure 2. Glulam configuration (sample ref. B-1)

Test Results

Table 1. results of the four-point bending test

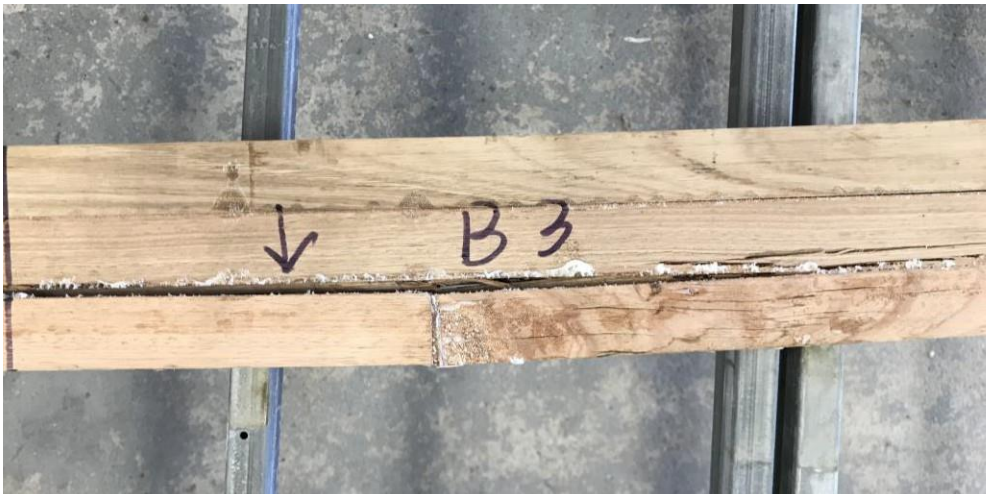
Sample	MOE (MPa)	MOR (MPa)	Ultimate load (kg)
A-1	16,376	53.1	2,044
A-3	15,625	62.9	2,532
B-1	14,420	56.3	2,172
B-2	15,722	55.2	2,790
B-3	15,145	29.3	1,162
Average	**15,458**	**51.4**	**2,140**

(a)

(b)

(c)

(d)



(e)

Figure 3. Samples failure modes after testing

Figure 4 Cross-section cut

Conclusions

The average bending stiffness (MoE) and bending strength (MoR) of 5 TasOak glulam beams is 15.5 GPa and 51.4 MPa. Sample B-3 shows shear failure in the glue line and low MoR. The finger joints in the glulam elements exhibited a good load bearing capacity in bending while glue line failure was observed in two samples (B-2 and B-3). More samples need to be produced and tested to characterise the mechanical properties of the glulam from TasOak. Plus, characterisation of mechanical properties of the lamination is also required. Delamination test to determine bonding performance is required to evaluate the shear strength of the glue line and determine effective gluing practice for reliable glulam production.

Quick provisional summary on testing FJ

1 Method

The boards were selected in such a way to insure about defect free timber portion to locate the finger joints. No grading or determination on MOE properties could be undertaken. The densities on both sides of the future finger joint has been determined. The finger joints were produced by a swiss glulam manufacturer. The pressure was adjusted to avoid crushing of the fingers but ensure that the joint is closed properly. Loctite HB S109 Purbond was used for both series and a 15/3,8 mm finger joint profile was applied. Two series with similar density distribution were produced. For series 1 the standard process as for spruce was applied. For series 2 a special hardwood process developed by the glulam manufacturer was applied. Series 3 represents the finger joints produced by CLTP at an earlier stage for the Dubai project. The tension tests were carried out at the laboratory of the BFH in Biel. The tests were done along EN 408:2010&A1:2012. The exact measurements and positioning of the finger joint are shown in Figure 1. The load was applied force controlled to failure and the speed was chosen that it could be expected that failure occurs in 300 ± 120 seconds (Table 1).

Table 1: Parameters of the three series

	Series 1	Series 2	Series 3
adhesive	Loctite HB S109	Loctite HB S109	PUR
process	Softwood	Hardwood	CLTP
nominal dimensions	22 mm x 118 mm	23 mm x 118 mm	25 mm x 125 mm
loading speed	336 N/s	336 N/s	252 N/s
specimens tested	21	20	9

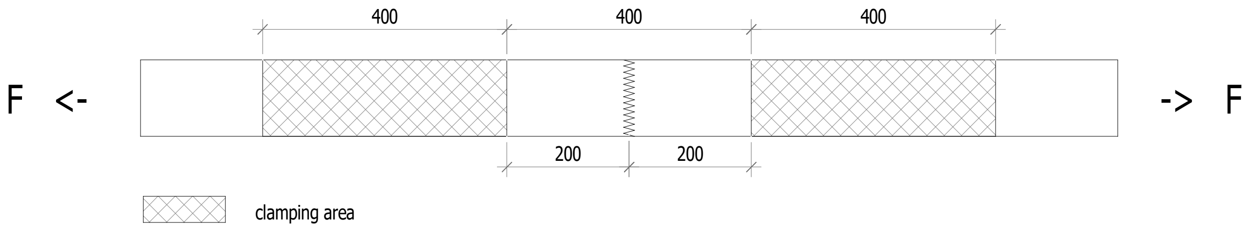


Figure 1: schematic sketch of the test setup

Figure 2: Specimen in the tension testing machine

2 Results

Some of the specimens failed in tension in the timber section, the failure was not influenced by the finger joints. These specimens are not considered in the analyses. However, most failures occurred in the region of / in the finger joints and therefore represent the strength of this connections (Figure 3). The tension strength achieved by series 1 and 2 is sufficient to produce glulam with of the strength class GL24 and GL28. The finger joints supplied by CLTP show clearly lower tension strength and is not sufficient to produce structural glulam (Figure 4 and Table 2)

Figure 3; Typical failure of the finger joints in series one and two

Table 2 shows the results from the tension tests on finger joints. For the calculation of the 5%-percentile the number of the specimens was considered as required in EN 14358:2016 as proposed for initial type testing, assuming a log-normal distribution of the tension strength of the finger joint. A student-t-test showed no significant difference between the two series produce in Switzerland. The 5%-percentile value of these two series are nearly equal, the coefficient of variation for the hardwood process is higher compared to the softwood process if the outlier in the softwood process is not considered.

Table 2: Overview of the results

	Series 1	**Series 1**	**Series 3**
Number of specimens considered	17	17	9
Average tension strength	43.8 MPa	48.3 MPa	18.7 MPa
5%-percentile	28.6 MPa	28.1 MPa	10.8 MPa
min	30.0 MPa	30.6 MPa	12.9 MPa
max	69.6 MPa	69.0 MPa	25.0 MPa

No grading routine could be undertaken to separate the timber forming the specimens into 2 or 3 stress grades. The results are obtained on ungraded timber. The boxplot (Figure 4) still clearly shows that the hardwood-process (series 2) enables for higher tension strength than the softwood process. However, this potential can only be realized if the 5%-percentile can be increased by avoiding failure at “low” strength in optimising the MOE and density profiles of the boards. In order to estimate the cause for the “low” values in series 2 a larger testing campaign with stress graded boards with a finally established grading routine on the finally used resource would be necessary (stress grading criteria needed). Figure 4 also clearly shows the significant difference between the finger joints produced using shorter fingers and the ones using longer fingers, both produced in Switzerland. It must be kept in mind that Schilliger Holz (Dubai project) came up with some doubts regarding the quality of gluing from this early stage finger joint production.

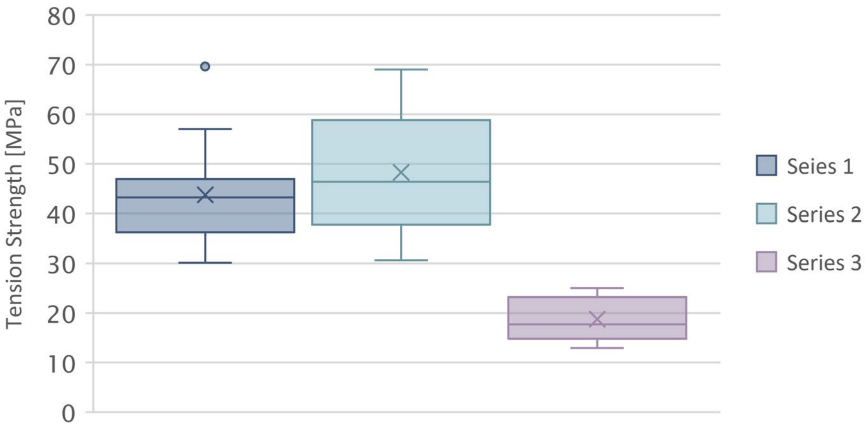


Figure 4: Boxplot of the different series where the x represents the average and the box the quartile and the line in the box the median.

It can be concluded from this small test series that eucalyptus nitens has a promising potential if the right finger joint profile and the right process are used.

M. Lehmann / C. Sigrist / A. Zare
16th November 2020

Construction and Building Materials 349 (2022) 128774

Contents lists available at ScienceDirect

Construction and Building Materials

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

Study of the relationship between flatwise and edgewise modulus of elasticity of plantation fibre-managed *E. nitens* sawn boards

Jian Hou [a,*], Assaad Taoum [a], Gregory Nolan [b], Nathan Kotlarewski [b]

[a] School of Engineering, University of Tasmania, Hobart TAS 7005, Australia
[b] Centre for Sustainable Architecture with Wood (CSAW), University of Tasmania, Launceston TAS 7250, Australia

ARTICLE INFO

Keywords:
E. nitens
Modulus of elasticity
Stiffness
Bending test
Edgewise MoE
Flatwise MoE
Visual features

ABSTRACT

This study investigated the relationship between flatwise and edgewise modulus of elasticity (MoE) of plantation fibre-managed *E. nitens* sawn boards. 331 boards were used to build a complete picture of this resource by measuring the density, moisture content, and static edgewise MoE. Then, 147 boards were tested for static flatwise MoE. Results showed that average static flatwise MoE is highly linearly related to static edgewise MoE. The average flatwise MoE could be predicted through the linear relationship considering the contribution of the width of the boards. The R^2 value of this linear regression formula is 0.9.

1. Introduction

In Australia, around 75 percent of hardwood plantations are either *E. globulus* (southern blue gum, 53 %) or *E. nitens* (shining gum, 25 %) [1]. In Tasmania, a substantial amount of plantation fibre-managed *E. nitens* is grown generally without thinning, pruning or similar silvicultural intervention and then harvested predominantly for export as chips, fibre or peeler logs. Given the size and availability of this resource, the wood products industry is seeking ways of convert it into structural board or mass laminated timber products suitable for building construction. Due to the extent of strength reducing characteristics in this material, boards recovered from it must undergo stringent grading before they can be used in fit-for-purpose timber products [2].

Although structural applications of softwood and some hardwood species have been widely researched, research on the mechanical properties of *E.nitens* is needed for a comprehensive understanding of its structural performance. Timber is a natural material, and its properties are influenced by the environment and genetics of the growing trees, and the wood in these trees has diverse properties that vary with the material's age and silvicultural history [3]. Fibre-managed *E. nitens* grown in unthinned and unpruned plantation stands has unique features that affect its mechanical properties including the stiffness of the boards [4].

Mass laminated timber products such as glued laminated timber, cross-laminated timber, and nail-laminated timber are assembled from boards by joining them with adhesive or mechanical fasteners. The stiffness of sawn boards, especially the flatwise orientation, has a substantial influence on the strength of the mass laminated timber products to which they contribute. Therefore, applying fibre-managed *E.nitens* in commercial structural products requires a robust understanding of the stiffness of raw material boards.

Some studies have been conducted to obtain a better understanding of the stiffness of fibre-managed *E.nitens*. Derikvand et al. characterised the physical and mechanical properties of this species [2]. They tested clear wood samples using a three-point bending test and established that edgewise MoE is 10377.7 MPa. Farrell et al. applied Acoustic wave velocity (AWV) to sort plantation grown *E. nitens* by comparing stiffness, bending and shear strength, and hardness [5]. Blackburn et al. studied stiffness and checks of *E. nitens* sawn boards using a genetic analysis [6]. McGavin et al. tested veneer samples by the acoustic method and found

Abbreviations: AIC, Akaike's information criterion; ANOVA, Analysis of variance; AWV, Acoustic wave velocity; CI, Confidence interval; cor, Correlation coefficient; D, Density; df, Degrees of freedom; *E. globulus*, *Eucalyptus globulus*; *E. nitens*, *Eucalyptus nitens*; F_{ave}, Mean value of average static flatwise MoE; FM, Static average flatwise MoE; F_{max}, Maximum value of average static flatwise MoE; F_{min}, Minimum value of average static flatwise MoE; LL, Log-likelihood; MAE, Mean absolute error; MANOVA, Multi-factor analysis of variance; MAPE, Mean absolute percentage error; MC, Moisture content; MoE, Modulus of Elasticity; Q-Q plot, Quantile-quantile plots; $\mathbf{S_d}$, Standard deviation; V, Visual features; VSG, Visual stress-grading; W, Width of the sawn board; $\boldsymbol{\mu}$, Mean value.

* Corresponding author.
E-mail address: jian.hou@utas.edu.au (J. Hou).

https://doi.org/10.1016/j.conbuildmat.2022.128774
Received 9 May 2022; Received in revised form 29 July 2022; Accepted 10 August 2022
Available online 16 August 2022

that *E. nitens* produced the most 'efficient' wood in comparison with the other five Australian plantation hardwoods, with the best stiffness to weight ratio [3]. Balasso et al. found the correlation between dynamic MoE and static edgewise MoE of plantation *E. nitens* [7]. Ettelaei et al. found good correlation between the MOE values obtained from machine stress grading and four-point bending test [8].

However, all the existing research on fibre managed *E.nitens* are on static edgewise MoE value or the dynamic MoE value. No research on the static flatwise MoE have been reported. Timber element as a component in glulam are in flatwise in most cases. That means the key parameter is the static flatwise MoE which influence the glulam performance directly, not the static edgewise MoE or dynamic flatwise MoE. Testing static flatwise stiffness can be a time-consuming work both in the lab and in the factory. Therefore, if a correlation between static flatwise MoE and static edgewise MoE of this species could be established, it will benefit both industry and academia.

The relationship between flatwise and edgewise MoE contributes to a better understanding of the raw material. Research into this relationship has been conducted effectively with Spruce - a widely used the raw material. Research into this relationship has been conducted effectively with Spruce - a widely used feedstock of mass laminated timber products. Steffen et al. employed regression functions to estimate the edgewise MoE of spruce based on the flatwise MoE, and also investigated the influence of structural wood characteristics and grading parameters on the relationship between flatwise and edgewise bending MoE [9]. Burger and Glos used Spruce in their examination of the relationships between MoE in bending and in tension as well as between MoE in edgewise and flatwise [10]. X-ray and laser scanning have been used in predicting the stiffness of sawn Spruce. Olsson et al. used a laser scanner to identify the fibre orientation on the face and edge surfaces of Spruce and calculated the edgewise bending stiffness profile and longitudinal stiffness profile by integrating grain angle information over cross-sections to predict timber bending strength [11].

A useful correlation between flatwise MoE and visual features is crucial to streamline *E.nitens* board production and grading. The processes included in Australian Standard 2082–2007 are not suitable for fibre-managed *E.nitens* and traditional visual grading methods based on the assumptions in this standard have proved to be ineffective for this resource [7]. Therefore, in this study, the relationship between static flatwise MoE and visual features was investigated in an attempt to find an effective grading method for fibre-managed *E.nitens*.

A study of the static flatwise and edgewise MoE of *E. nitens* sawn boards may improve mechanical strength grading technology and provide a more reliable stiffness relationship for the stochastic modeling of sawn boards or wooden composites, such as glued laminated timber and cross-laminated timber. This study aimed to contribute to a better understanding of the relationship between flatwise and edgewise MoE of plantation fibre-managed *E. nitens* sawn boards. The secondary aims of this study were to:

- Obtain the edgewise MoE value distribution of the whole population.
- Develop and verify a linear regression model to predict the relationship between edgewise MoE and average flatwise MoE of visual graded back sawn boards.
- Investigate the impact of timber features and sawing method on the relationship of edgewise and average flatwise MoE.

2. Materials and methods

2.1. Materials

The material used in this study was recovered from a 21-year-old, fibre managed *E. nitens* plantation in southern Tasmania. Harvested logs were back-sawn in a production sawmill to maximise board recovery. Boards were racked and then air-dried to fibre saturation point in an industry drying yard. As *E.nitens* is a collapse-prone species, the boards were reconditioning in a steam chamber before final kiln drying.

A total of 331 boards were used in this study. The nominal widths of sawn boards were 70 mm, 90 mm, and 120 mm. The nominal thickness was 35 mm. Prior to testing, the moisture content and density of each board were measured. Width, length, and thickness were measured to assess individual board volume. A scale with an accuracy of 0.1 kg was used to weigh the boards. The nominal density of the boards equaled the weight divided by volume. The moisture content was measured by a Moisture Encounter Meter. The cumulative distribution of density and moisture content is shown in Fig. 1.

The whole pack of 331 boards was subjected to the four-point bending test to investigate the edgewise MoE distribution. In order to study the relationship between edgewise and flatwise MoE, subset A was set up. A total of 90 boards, 30 of each width, were selected based on their edgewise MoE value. The edgewise MoE was distributed between 10195.5 MPa and 19295.5 MPa. Two additional test subsets were set up to verify the prediction models. Subset B was used to verify the accuracy of the models in predicting the MoE values. This subset contained 45 randomly selected boards other than the mentioned 90 boards, with a width of 90 mm and 120 mm. Subset C was used to verify the accuracy of the models in predicting the MoE value of quarter-sawn boards. The angle of tangential grain to the faces of these boards are 60 degrees or more. This subset contained 12 boards with quarter-sawn patterns from among the 331 boards. The numbers of boards in the sets are summarised in Table 1.

2.2. Visual grouping

A total of 147 boards of all the three subsets were visually grouped, based on their features. Researchers found no difference in the average MoE of *E. nitens* sawn boards among visual grades in accordance with the hardwood visual grading standards AS 2082–2007 [7].

Therefore, in this study, the requirements of the Standard [12] were only used as the threshold. Boards were sorted into a graded group and three non-graded groups. All the boards that met the minimum requirements of the structural grade were assigned to the graded group. The boards with long checks (more than half of the board length) were placed in the non-graded checks group. The boards with oversize knots (diameter greater than three-eighths of the board width) were allocated to the non-graded knots group. The boards with pith were placed to the non-graded pith group. The numbers of boards in different groups were summarised in Table 2.

2.3. MoE measurement

2.3.1. Edgewise MoE

The edgewise MoE of each board was determined by the four points bending test with a span to depth ratio of 18 according to AS/NZS 4063.1: 2010 [13]. The difference in MoE between the two faces of a timber board is negligible [9]; hence, in this study, the edgewise bending test was only performed one time per board, in which the weaker sides were unified to be positioned on the compression side. One edgewise bending test was conducted per board. The test setups of bending tests are shown in Fig. 2. The edgewise MoE was calculated using the following equation:

$$E_{edge} = \frac{23}{108}\frac{\Delta Fl^3}{\Delta dbh^3} \tag{1}$$

Where:

E_{edge} = Edgewise MoE,
ΔF = load at elastic region (N),
Δd = corresponding deformation at elastic region (mm),
l = span (mm),
h = specimen height (mm),
b = specimen width (mm).

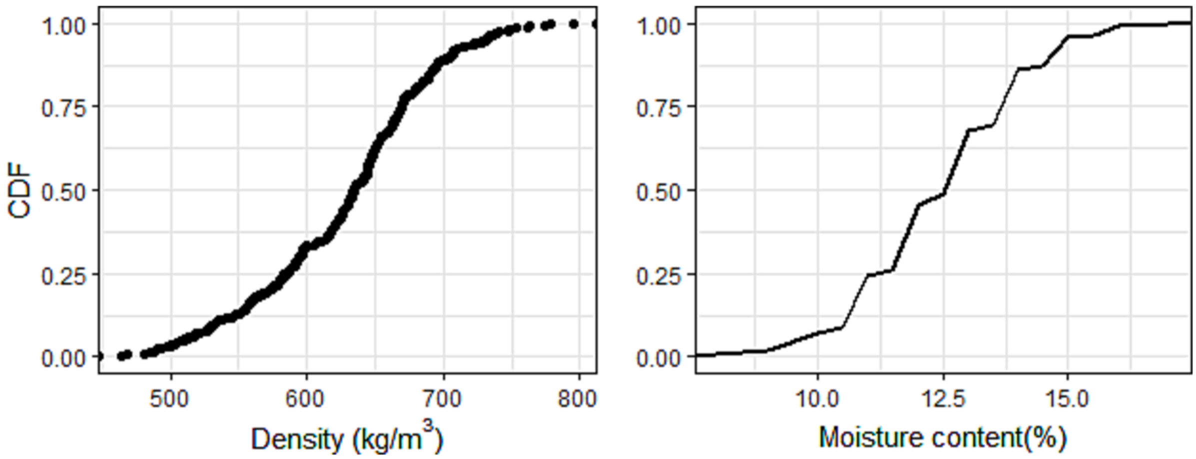


Fig. 1. Cumulative distribution of density and moisture content.

Table 1
The number of boards in the sets.

Model	Total number	Width A(90 mm)	Width B(120 mm)	Width C(70 mm)
Whole pack	331	74	140	58
Subset A	90	30	30	30
Subset B	45	37	8	/
Subset C	12	5	4	3

Table 2
The number of boards in different visual groups.

Model	Visual Groups			
	Graded	Checks	Knots	Pith
Subset A	39	18	16	17
Subset B	22	2	14	7
Subset C	4	1	2	5

2.3.2. Flatwise MoE

A total of 147 boards in three subsets were tested by the static three points bending test according to ASTM D 198–15 [14]. The boards were tested every 100 mm. Each board was tested 14 or 17 times depends on the length of the board. In the static three points bending test, the span was 600 mm, and the span to depth ratio is 17.1. The flatwise MoE was calculated by the following equation:

$$E_{i,flat} = \frac{\Delta F l^3}{\Delta d 4 b h^3} \tag{2}$$

$$E_{flat} = \frac{\sum_1^n E_{i,flat}}{n} \tag{3}$$

Where:
$E_{i,flat}$ = flatwise MoE for the "i" section,
E_{flat} = average flatwise MoE for each board,
n = the total number of the tested sections for one board.

The possibility of some damage from the edgewise testing influencing the flatwise testing was considered and all flatwise samples avoided any breaks or damage from previous edgewise testing. The test setups of bending tests are shown in Fig. 3.

2.4. Statistical analysis

Statistical analyses were conducted using statistical software R studio. The level of significance was set at 5 % (P < 0.05).

2.4.1. Statistical tests

- Kolmogorov-Smirnov test were conducted to verify the normality distribution of edgewise MoE for the whole pack. This test is more appropriate method for large sample size (n ≥ 50) compared with the

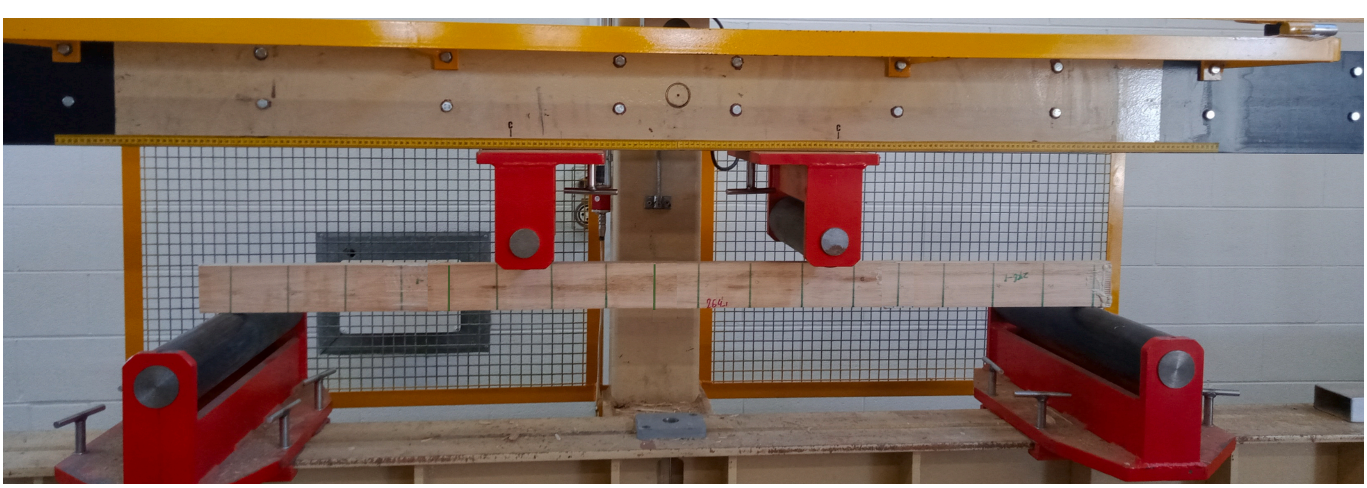


Fig. 2. Four points bending tests setup (edgewise).

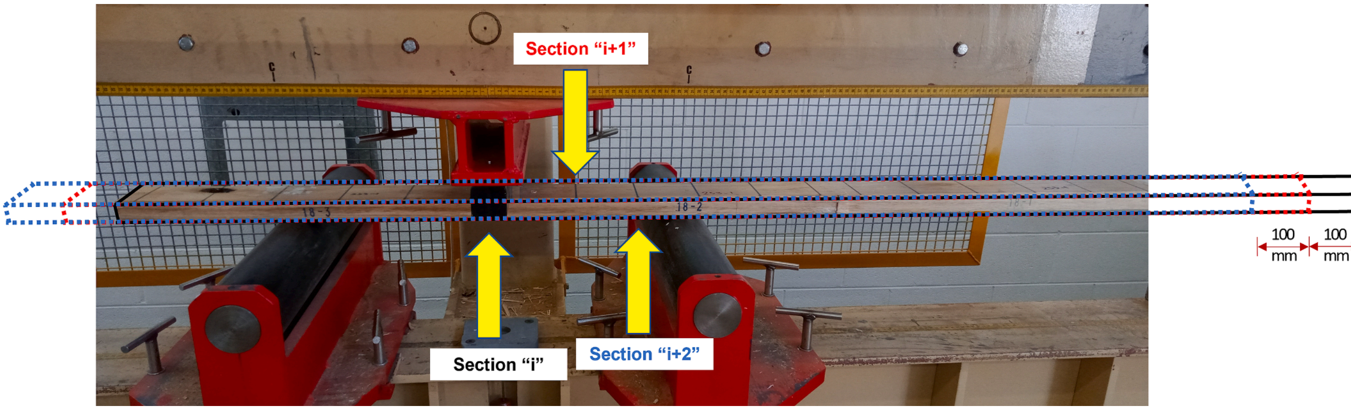


Fig. 3. Three points bending tests setup (flatwise).

Shapiro–Wilk test [15]. The quantile–quantile (Q-Q) plots was also produced to verify the distribution.

- Pearson's test was conducted to calculate the correlation coefficient of covariates, including density and moisture content, with static edgewise MoE and average flatwise MoE, respectively.
- Analysis of variance (ANOVA) was used to detect the significance of the difference of flatwise MoE and density among visual groups. Tukey's test was conducted as post-hoc tests to compare the differences among groups.

2.4.2. *Steps of MoE prediction*

To predict the MoE values by using wood properties (density, moisture content, width, visual features group) as predictors, the statistical analysis steps are:

- Build the model nest considering all the factors and covariates by general linear regression.
- Calculate the Akaike's information criterion (AIC) values of all the models to select the best model.
- Refit the best model to predict the MoE values.

2.4.3. *General linear regression*

Linear regression was conducted to predict the MoE values. There was no interaction considered because all the parameters are independent physical properties. There was no random effect considered. Predictors are a combination of factors (categorical) and covariates (continuous). D and MC were covariates.

A) Edgewise MoE models.

To predict edgewise MoE, the general linear model was established considering three factors and covariates, including W, D, and MC.

B) Flatwise MoE models.

To predict flatwise MoE, the general linear model was established considering four factors and covariates, including W, D, MC, and V.

C) Relationship models.

To establish the relationship between edgewise MoE and flatwise MoE, the general linear model was fitted considering four factors and covariates, including W, D, MC, and V.

2.4.4. *Model selection*

Akaike's information criterion (AIC) was used as the criterion for model selection. The candidate models including all the significant factors and covariates were ranked by AIC value. AIC value is calculated by log-likelihood (LL) and the number of estimated parameters (K), $AIC = 2 - lnL + 2K$. The model with the smallest AIC value is the best model. The number of candidate models is 2^m, in which "m" is the quantity of factors and covariates.

The difference between AIC of each model and the lowest AIC was calculated, $\Delta AIC = AIC - \min(AIC)$. The candidate models having an ΔAIC value within 6 were listed for selection. A factor being in all the candidate models is a strong support for that factor to be a predictor.

In this study, the models with the smallest AIC value were selected to predict the MoE values.

3. Results

3.1. *Edgewise MoE*

The static edgewise MoE values of the 331 boards presented a normal distribution. Fig. 4 showed the static edgewise MoE distribution, and the edgewise MoE value averaged 13742.6 ± 2707.4 MPa (n = 331).

The Kolmogorov-Smirnov test was conducted to confirm the distribution, and the null hypothesis was rejected. The test indicated that the static edgewise MoE values follow a normal distribution, ($D(331) = 0.04$, $p = 0.74$). The quantile–quantile (Q-Q) plots for the data set showed the same conclusion as the Kolmogorov-Smirnov tests (Fig. 5). The Q-Q plot had both the ends to deviate from the straight line and its center to follow a straight line approximately, which means the data sets follow a normal distribution.

Potential application prospects of manufacturing mass timber products by using *E. nitens* were observed. In the whole package of sawn boards, an estimated 56.8 % of boards had a static edgewise MoE value higher than 13300 MPa, and an estimated 12.7 % of boards had a value higher than 16700 MPa.

Pearson's tests revealed the correlation coefficient of the linear relationship between static edgewise MoE and density and moisture content. Density was highly correlated with static edgewise MoE (Pearson's test: $df = 329$, $cor = 0.70$, $P < 0.05$); the correlation between moisture content and static edgewise MoE was slightly weaker (Pearson's test: $df = 329$, $cor = 0.57$, $P < 0.05$).

Considering one factor W and two covariates, D and MC, the model nest was built. There were 8 models in this best. The candidate models with the $\Delta AIC<6$ were ranked by the AIC value in Table 3. The covariates, D and MC, occurred in all the candidate models. Meanwhile, the model with D and MC had the smallest AIC value. Therefore, this model was selected.

The general linear model was refitted to predict the static edgewise MoE value (Fig. 6). The linear regression parameters were listed in Table 4.

The regression function showed as following equation for the static edgewise MoE values determined in this research was established based on the D and MC.

$$EM = -5587.6 + 24.3D + 320.9MC \tag{4}$$

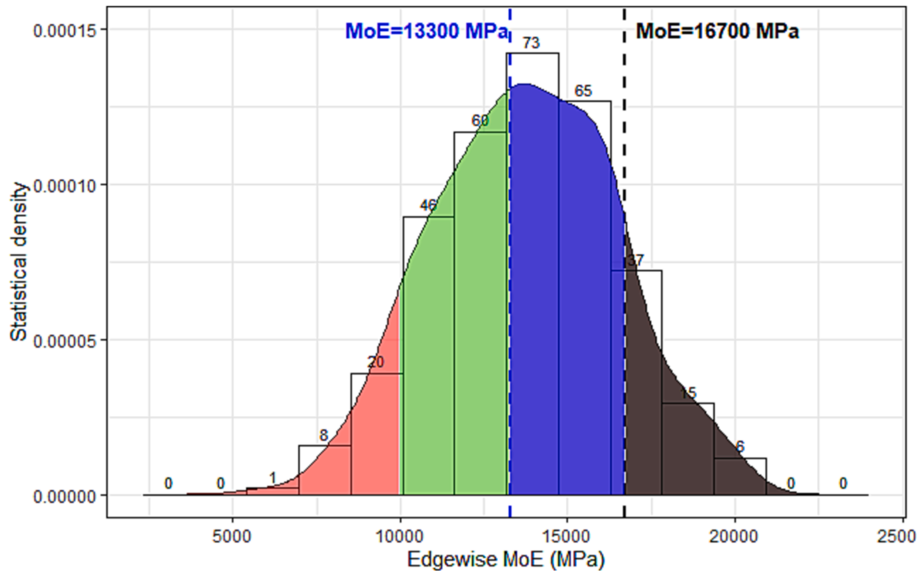


Fig. 4. Static edgewise MoE distribution (n = 331).

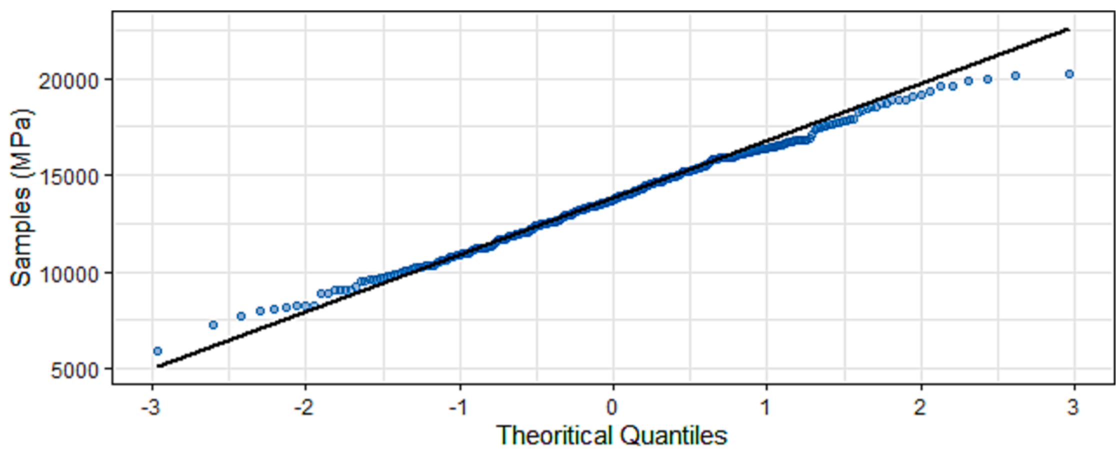


Fig. 5. The quantile–quantile (Q-Q) plots for the edgewise MoE (n = 331).

Table 3
Candidate edgewise models ranked by AIC values.

Model	K	LL	AIC	ΔAIC
1 + D + MC	4	−2967.0	5942.1	0.0
1 + D + MC + W	7	−2966.8	5947.9	5.82

Notes:
No interactions were considered.
K is the number of estimated model parameters.
LL is the maximum loglikelihood.
AIC is Akaike's Information Criterion.
ΔAIC is the difference between the AIC value of the model and the lowest AIC value calculated.

3.2. Flatwise MoE

The static flatwise MoE value varied with visual features (ANOVA, $F_{3,266} = 27.9$, $P < 0.05$). The average static flatwise MoE mean value (F_{ave}) of graded boards was 13631.2 MPa. The presence of oversized knots decreased this value by 638.8 (Tukey's test, t value = -0.90, $P = 0.80 > 0.05$), 95 % CI (-2043.2, 765.7) MPa. The presence of pith decreased it by 2255.1 (Tukey's test, t value = -3.26, $P < 0.05$), 95 % CI (-3627.0, −880.3) MPa. However, the presence of checks in boards increased this value by 2663.6 (Tukey's test, t value = 3.93, $P < 0.05$), 95 % CI (1315.6, 4011.6) MPa. The maximum (F_{max}) and minimum (F_{min}) values presented the same trend as the average value (Fig. 7).

At the same time, the mean density of graded boards was 607.3 kg/m^3 (Fig. 7). while the mean density of the group with knots was 21.0 kg/m^3 higher (Tukey's test, t value = 1.26, $P = 0.58 > 0.05$), 95 % CI (-12.0, 54.0); the density of the group with pith decreased by −10.8 kg/m^3 (Tukey's test, t value = -0.66, $P = 0.91 > 0.05$), 95 % CI (-43.1, 21.6); and mean density of checked boards increased by 35.9 kg/m^3 (Tukey's test, t value = 2.25, $P = 0.12 > 0.05$), 95 % CI (4.13, 21.56). The differences were not statistically significant.

The average static flatwise MoE value was smaller than the average static edgewise MoE value (E_{aver}). For the graded group and checks group, the difference between the two values was 287.4 MPa and 235.9 MPa respectively. For the boards with oversize knots, the E_{aver} value was 350.7 MPa larger than F_{ave}. The difference for the pith boards was 899.1 MPa.

Pearson's tests revealed the correlation coefficient of the linear relationship between average static flatwise MoE value and density and moisture content. Density was highly correlated (Pearson's test: df = 88, cor = 0.78, $P < 0.05$); the correlation between moisture content and static flatwise MoE was slightly weaker (Pearson's test: df = 88, cor =

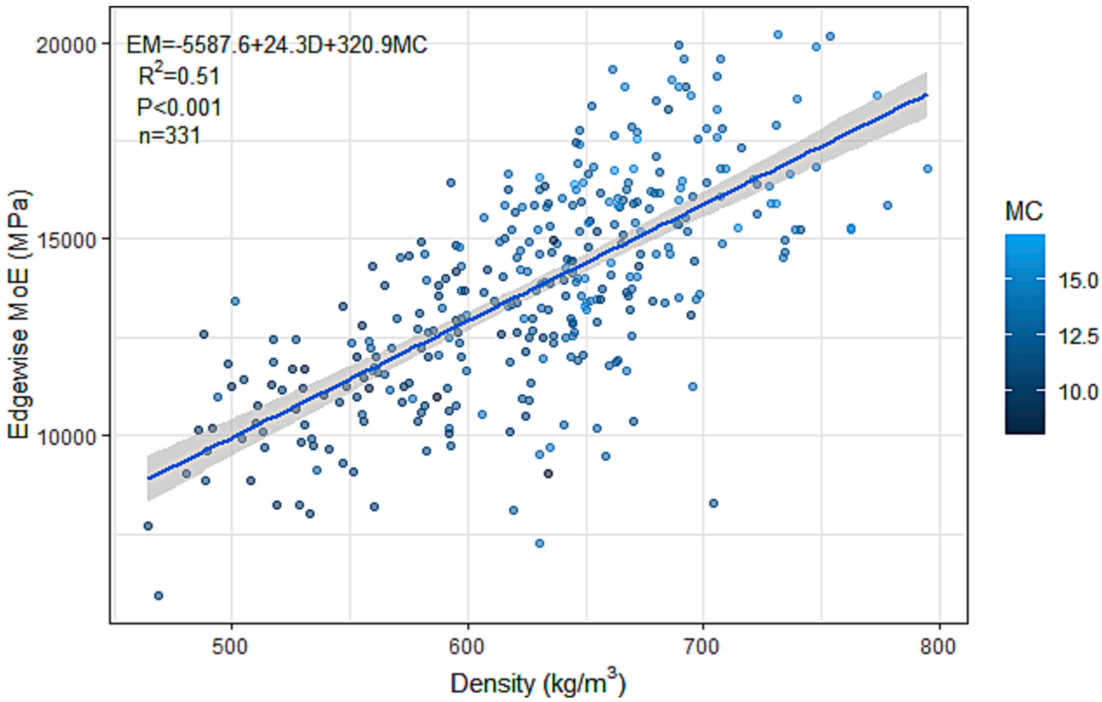


Fig. 6. Relationship between density and static edgewise MoE (filled circles). The straight line is static edgewise MoE estimated by D and MC. And the grey region depicts the 95% confidence interval for the mean.

Table 4
Parameters of selected edgewise model.

R^2	df	Intercept		D		MC	
		P-value	F- value	P-value	F-value	P-value	F-value
0.51	328	<0.05	−5587.6	<0.05	24.3	<0.05	320.9

0.64, $P < 0.05$).

Considering two factors (W, V) and two covariates (D, MC), the model nest was built. There were 16 models in this best. The candidate models with the ΔAIC<6 were ranked by the AIC value in Table 5. The covariates, D and V, occurred in all the candidate models. Meanwhile, the model with D and V had the smallest AIC value. Therefore, this model was selected.

The linear regression analysis was performed to predict the static

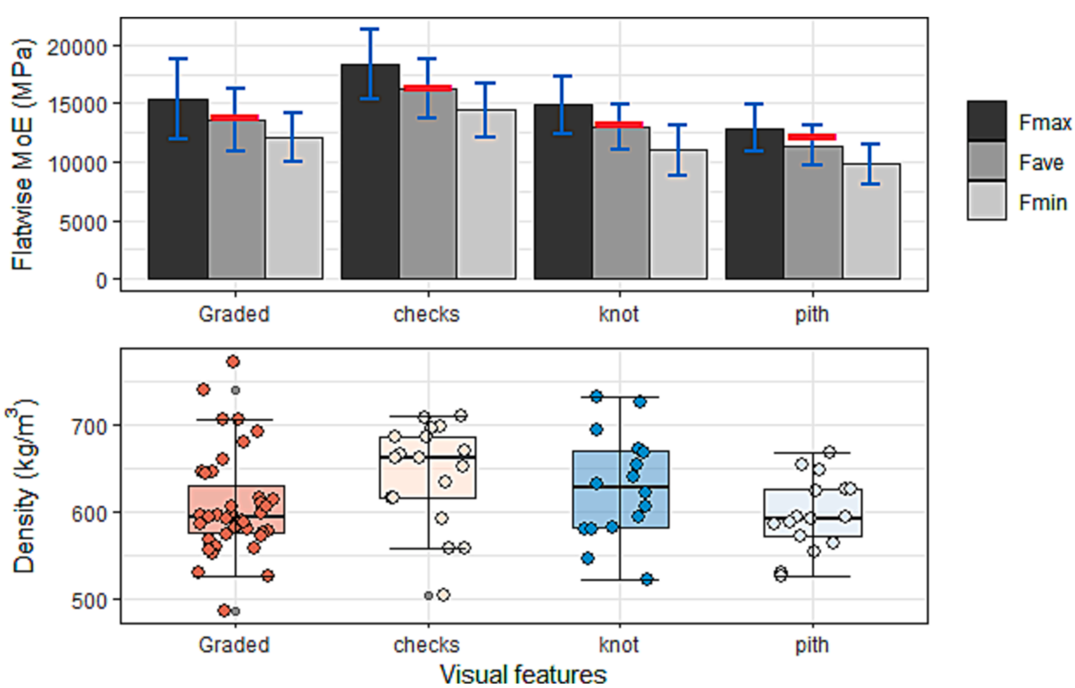


Fig. 7. Static flatwise MoE mean values (filled bars) and standard deviation among visual features. The horizontal short lines (blue) are standard deviation bars. The horizontal lines (red) are static edgewise MoE mean values. Density (MC being adjusted to 12%) among visual features. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 5
Candidate flatwise models ranked by AIC values.

Model	K	LL	AIC	ΔAIC
1 + D + V	6	−775.5	1564.0	0.0
1 + D + V + MC	7	−774.8	1565.0	1.0
1 + D + V + W	8	−775.2	1568.1	4.2
1 + D + V + W + MC	9	−774.4	1569.1	5.1

Notes: Same as Table 3.

average flatwise MoE value by building up the selected model (Fig. 8). The linear regression parameters were listed in Table 6.

The regression function showed as the following equation for the static average flatwise MoE values determined in this research was established based on the density and the visual features.

$$FM = 34.8D - \begin{cases} 7503.4 & Graded \\ 6087.1 & Checks \\ 8873.2 & Knots \\ 9383.2 & Pith \end{cases} \tag{5}$$

3.3. Relationship between edgewise MoE and average flatwise MoE

To explore the relationship between edgewise and flatwise MoE, flatwise MoE value (FM) was considered as a covariate with D, MC, W, and V. Pearson's tests revealed the correlation coefficient of the linear relationship between average static flatwise MoE value and edgewise MoE (Pearson's test: df = 88, cor = 0.94, $P < 0.05$).

Considering two factors (W, V) and three covariates (D, MC, and FM), the model nest was built. There were 32 models in this best. The candidate models with the ΔAIC<6 were ranked by the AIC value in Table 7. The covariates FM and factor W occurred in all the candidate models. Meanwhile, the model with FM and W had the smallest AIC value. Therefore, this model was selected.

The linear regression analysis was performed to predict the static edgewise MoE value by considering flatwise MoE (Fig. 9). The model performed well in predicting average flatwise MoE (Linear regression; R2 = 0.90, df = 86, $P < 0.05$). The linear regression parameters were listed in Table 8.

The regression function showed as the following equation for the static edgewise MoE values determined in this research was established based on the relationship.

$$EM = 0.92FM + \Delta, \Delta = \begin{cases} 1920.8 & Width\ A\ (90\ mm) \\ 1418.7 & Width\ B\ (120\ mm) \\ 1077.4 & Width\ C\ (70\ mm) \end{cases} \tag{6}$$

Meanwhile, the relationship could be used to predict static average flatwise MoE, and the regression function showed as the following equation.

$$FM = (EM - \Delta)/0.92, \Delta = \begin{cases} 1920.8 & Width\ A\ (90\ mm) \\ 1418.7 & Width\ B\ (120\ mm) \\ 1077.4 & Width\ C\ (70\ mm) \end{cases} \tag{7}$$

3.4. Verification of the models

Two subsets (B and C) were used to evaluate the prediction models. The prediction model based on the relationship between two MoE values (Eq. (6)) performed better than the model based on density in predicting the static edgewise MoE (Eq. (4)). For subset A, the mean absolute error (MAE) was reduced from 1459.9 to 561.4 MPa by using Eq. (6) instead of Eq. (4), and the mean absolute percentage error (MAPE) was reduced from 10.1 % to 4.0 %. The effect was observed on both two test data sets (subsets B and C) (Table 9).

Meanwhile, the relationship model (Eq. (7)) performed better than the model based on density and visual features (Eq. (5)) in predicting the static average flatwise MoE. For subset A, the mean absolute error was reduced from 1090.0 to 610.2 MPa by using Eq. (7) instead of Eq. (5), and the mean absolute percentage error was reduced from 8.1 % to 4.5 %. The effect was observed on both two test data sets (subsets B and C) (Table 10).

4. Discussion

4.1. Sawing pattern

Subset C was set up to verify the accuracy of the models in predicting the MoE value of quarter-sawn boards. For Eqs. (4) and (5), the MAPE value of subset C increased over subset A. Meanwhile, the difference of MAPE value of Eqs. (6) and (7) between subset A and subset C was very small.

Scholars reported results on the impact of sawing methods on the

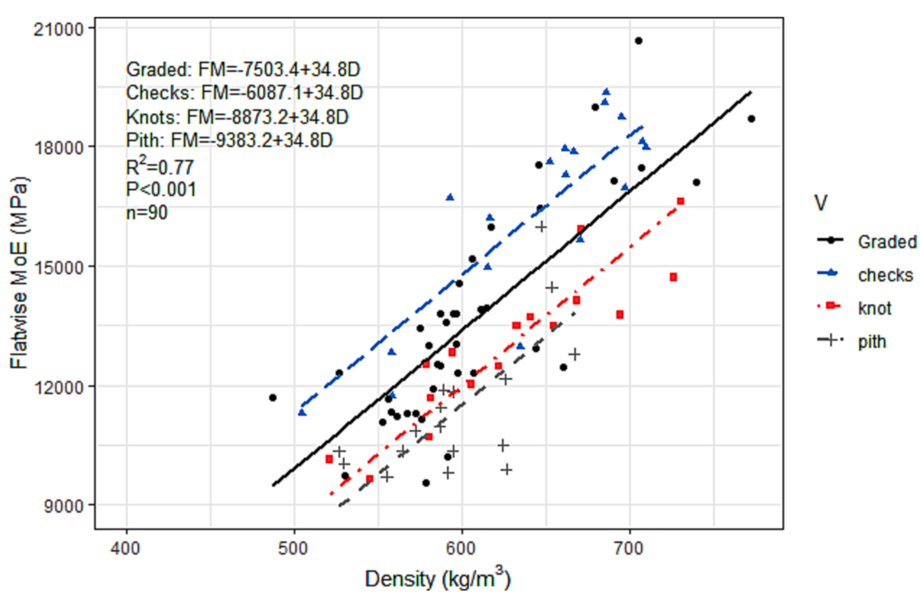


Fig. 8. Relationship between density and static average flatwise MoE (filled shapes). Straight lines are static flatwise MoE estimated by density for different visual features groups of boards.

Table 6
Parameters of selected flatwise model.

R^2	df	Intercept		D		V-Checks		V-Knots		V-Pith	
		P-value	F- value	P-value	F- value	P-value	F- value	P-value	F- value	P-value	F- value
0.77	85	<0.05	−7503.4	<0.05	34.8	<0.05	1416.3	<0.05	−1369.8	<0.05	−1879.8

Table 7
Candidate relationship models ranked by AIC values.

Model	K	LL	AIC	ΔAIC
1 + FM + W	5	−732.983	1476.7	0
1 + FM + W + MC	6	−732.092	1477.2	0.52
1 + FM + W + D	6	−732.700	1478.4	1.73
1 + FM + W + V	8	−730.694	1479.2	2.49
1 + FM + W + D + MC	7	−732.068	1479.5	2.82
1 + FM + W + MC + V	9	−729.855	1480.0	3.28
1 + FM + W + D + V	9	−730.574	1481.4	4.72
1 + FM + W + D + MC + V	10	−729.855	1482.5	5.82

Notes: Same as Table 3.

properties of sawn boards. Sawing method has a great influence on structural sawn boards, including volume yield [16], distortion performance before drying [17], shear properties [18], and bending properties [19]. However, McKimm et al. claimed that sawing method only influenced the amount of bow in freshly sawn plantation grown 20-year-old *E. nitens* boards [20]. In this study, the sawing pattern did not affect the relationship between edgewise MoE and flatwise MoE. Eqs. (6) and (7) could provide accurate predictions of quarter-sawn boards. The density-based Eqs. (4) and (5) presented a larger prediction difference between sawing pattern subsets than Eqs. (6) and (7). The board orientation due to sawing method determines the percentage of juvenile wood. The density of juvenile wood is relatively small. This means the density distribution of back-sawn and quarter-sawn boards are different. In addition, quarter-sawn boards present less face checking, but checks occur internally [21]. Therefore, the density-based prediction formula

Table 9
Summary of the evaluated parameters for static edgewise MoE prediction.

Terms	n	Equation (4)		Equation (6)	
		MAE	MAPE	MAE	MAPE
Subset A	90	1459.9	0.101	561.4	0.040
Subset B	45	1751.9	0.139	1004.6	0.077
Subset C	12	1428.6	0.115	507.3	0.042

Notes: The unit of MAE is MPa.
"n" represents the number of the boards in the corresponding data set.

Table 10
Summary of the evaluated parameters for static average flatwise MoE prediction.

Terms	n	Equation (5)		Equation (7)	
		MAE	MAPE	MAE	MAPE
Subset A	90	1090.0	0.081	610.2	0.045
Subset B	45	1633.1	0.129	1092.0	0.085
Subset C	12	1410.8	0.122	551.4	0.050

Notes: Same as Table 9.

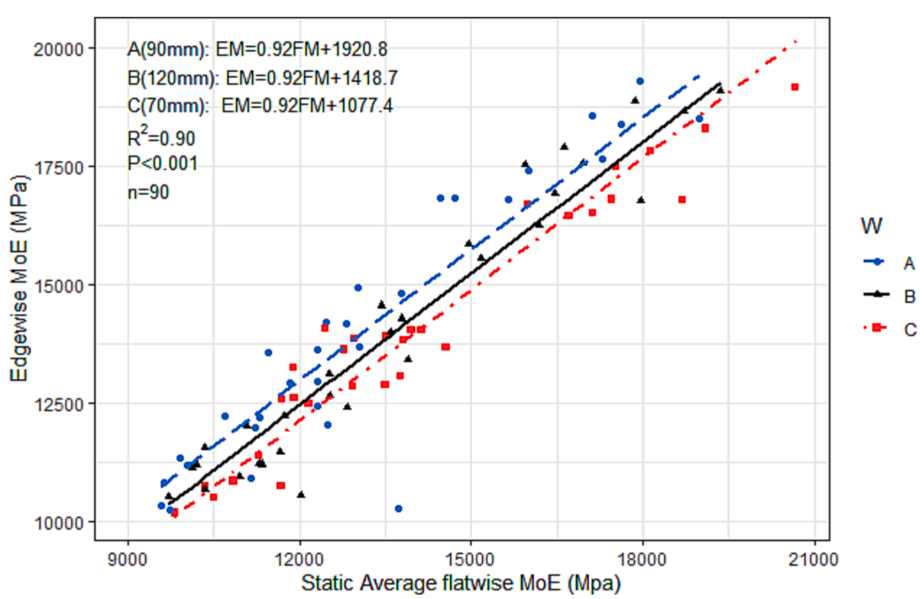


Fig. 9. Relationship between static edgewise MoE and static average flatwise MoE (filled shapes). Straight lines are static edgewise MoE estimated by static average flatwise MoE for different width groups of boards.

Table 8
Parameters of selected relationship model.

R^2	df	Intercept		FM		W-B		W-C	
		P-value	F- value	P-value	F- value	P-value	F- value	P-value	F- value
0.90	86	<0.05	1920.8	<0.05	0.92	<0.05	−502.2	<0.05	−843.4

performs worse on quarter-sawn boards.

It is essential to investigate the influence of sawing patterns on volume yield, distortion, and mechanical properties in order to get a better understanding of plantation *E.nitens* and streamline the value-added application. The scale of subset C was small. A full-scale sawing study would provide more comprehensive results in terms of comparing the sawing method of *E. nitens*.

4.2. Width

Width plays a role in the relationship of MoE in the two directions. In section 3.3, Eqs. (6) and (7) considering the width-based correction coefficient showed satisfactory prediction results. This indicates a considerable influence of shear deformation in determining the MoE value. Shear deformation is part of the deflection of beams in addition to the bending deformation [22]. According to Timoshenko's beam theory, the shear deformation decreases with decreasing stiffness of the beam. Usually, the span-depth ratio is controlled as an important indicator of stiffness [23]. In terms of edgewise MoE, the effect of shear deformation for different widths is theoretically the same as the span-width ratio is set as 18.0 for all the boards based on Australian standard AS/NZS 4063.1: 2010. However, in terms of flatwise MoE, a uniform span-depth ratio cannot eliminate the difference in shear deformation between boards of different widths. The span-thickness ratio for the flatwise bending test was 17.1 without considering width. This caused different shear deformations among the width groups. Therefore, the influence of width needs to be considered in the predicted model. Further study could be conducted to investigate the accurate influence of the shear deformation on determining the flatwise MoE.

4.3. Visual features

Current Australian visual grade standard AS 2082–2007 has proven to be inefficient in grading the plantation fibre-managed *E. nitens*. Balasso et al. found that a high percentage of plantation *E. nitens* boards using VSG (visual stress-grading) were misclassified based on the edgewise MoE value [7]. A higher misclassified percentage has been found in this study based on the flatwise MoE value. In the subset A, 42 out of 90 boards were under-graded because of the presence of pith, checks, and oversized knots; 3 out of 90 boards were upgraded.

However, the visual features group combined with density utilised in predicting flatwise MoE has shown satisfactory results. The MAPE values for subset B and C were acceptable (Table 10).

Compared with the graded group that passed the VSG, each visual feature group that failed the VSG had an adjustment value. The predicted values of boards with pith were much lower than that of the graded group (Fig. 7). This occurred because the presence of pith means a high percentage of juvenile wood which has a lower density, and MoE value [24]. Meanwhile, the predicted values of boards with oversize knots were lower than that of the graded group (Fig. 7). Such results indicate that the interference of grain direction caused by oversize knots must influence the MoE value to a considerable extent [9]. In contrast, the predicted values of boards with checks increased over the graded group (Fig. 7). There is no report on the correlation between checks and stiffness of *E. nitens* sawn boards [6]. In this study, the checks were exposed surface checks observed running along the grain on the flat faces of boards. *E.nitens* has a relatively high tangential shrinkage and back-sawn boards tend to develop face checks during drying more readily than transitional or quarter-sawn board. While checks have no direct relationship to stiffness, the checks in boards appear to relate to higher density (Fig. 7) and on average, indicates that the board are more likely to come from the denser and stronger wood on the outside of the logs.

5. Conclusions

The bending test results of 331 *E. nitens* boards showed that the static edgewise MoE values conformed to a normal distribution. Potential application prospects of manufacturing mass timber products by using *E. nitens* were observed.

Both density and moisture content were statically significantly correlated to the static edgewise MoE, and Pearson's correlation coefficients are 0.70 and 0.57 respectively. A linear regression model was built to predict static edgewise MoE based on the density. However, the correlation coefficient $R^2 = 0.49$ was low. Even the linear combination of density and moisture content did not significantly increase the prediction quality.

Although the Australian visual grade standard is inefficient in grading plantation fibre-managed *E. nitens*, visual feature groups play a role in predicting the average static flatwise MoE. Density and the visual group were statistically significantly correlated to the average static flatwise MoE. A linear regression model considering density and the visual group was built up to predict average static flatwise MoE. The prediction quality was acceptable with the correlation coefficient $R^2 = 0.77$.

The relationship between edgewise and flatwise MoE was determined. Given any one of them, the other could be predicted. The prediction accuracy was high with $R^2 = 0.90$. Width has been considered because of the shear deformation. Further study could be conducted to investigate the influence of width on determining the flatwise MoE.

Two test subsets were used to verify the prediction accuracy of the models. The relationship model performed better than the factor-based models for predicting edgewise or flatwise MoE. In addition, the relationship model worked well on the quarter-sawn test set (subset C). A full-scale sawing study may provide more comprehensive results in terms of comparing the sawing method of *E. nitens*.

Funding

This work was supported by the National Institute For Forest Product Innovation (Grant number: NT016/NIF080).

CRediT authorship contribution statement

Jian Hou: Conceptualization, Methodology, Data curation, Writing – original draft, Visualization. **Assaad Taoum:** Investigation, Validation, Writing – review & editing. **Gregory Nolan:** Supervision, Writing – review & editing. **Nathan Kotlarewski:** Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgement

National Institute For Forest Product Innovation (NIFFPI) is acknowledged for funding this research (Grant number: NT016/NIF080). Jon Shanks is acknowledged for initiating the research questions investigated herein and for his mentorship throughout the project. Monica Cuskelly is acknowledged for guiding English writing. Malcolm Liehr and Ka Ki Yeung is acknowledged for testing assistant. The ARC Training Centre for Forest Value is acknowledged for preparing the sawn boards.

References

[1] ABARES, Australia's State of the Forests Report 2018. 2018.
[2] M. Derikvand, et al., Characterisation of Physical and Mechanical Properties of Unthinned and Unpruned Plantation-Grown Eucalyptus nitens H. Deane & Maiden Lumber, Forests 10 (2) (2019) 194.
[3] R.L. McGavin, et al., Stiffness and Density Analysis of Rotary Veneer Recovered from Six Species of Australian Plantation Hardwoods, BioResources 10 (4) (2015) 6395–6416.
[4] M. Derikvand, et al., Visual stress grading of fibre-managed plantation Eucalypt timber for structural building applications, Constr. Build. Mater. 167 (2018) 688–699.
[5] R. Farrell, T.C. Innes, C.E. Harwood, Sorting eucalyptus nitens plantation logs using acoustic wave velocity, Australian Forestry 75 (1) (2012) 22–30.
[6] D. Blackburn, et al., Stiffness and checking of Eucalyptus nitens sawn boards: Genetic variation and potential for genetic improvement, Tree Genet. Genomes 6 (5) (2010) 757–765.
[7] M. Balasso, et al., Development of non-destructive-testing based selection and grading strategies for plantation eucalyptus nitens sawn boards, Forests 12 (3) (2021).
[8] A. Ettelaei, A. Taoum, G. Nolan, Assessment of Different Measurement Methods/ Techniques in Predicting Modulus of Elasticity of Plantation Eucalyptus nitens Timber for Structural Purposes, Forests 13 (4) (2022).
[9] A. Steffen, C.J. Johansson, E.W. Wormuth, Study of the relationship between flatwise and edgewise moduli of elasticity of sawn timber as a means to improve mechanical strength grading technology, Holz als Roh - und Werkstoff 55 (4) (1997) 245–253.
[10] N. Burger, P. Glos, Relationship between modulus of elasticity in tension and bending for timber, Holz als Roh- und Werkstoff 53 (2) (1995) 73–74.
[11] A. Olsson, et al., Prediction of timber bending strength and in-member cross-sectional stiffness variation on the basis of local wood fibre orientation, Eur. J. Wood Wood Prod. 71 (3) (2013) 319–333.
[12] AS2082:2007, *Timber - Hardwood - Visually stress-graded for structural purposes*. 2007, SAI Gloal Limited under licence from Standards Australia Limited.
[13] AS/NZS4063.1:2010, *Characterization of structural timber Test methods*. 2010, SAI Gloal Limited under licence from Standards Australia Limited.
[14] ASTM(D198-15), *Standard Test Methods of Static Tests of Lumber in Structural Sizes*. 2015, World Trade Organization Technical Barriers to Trade (TBT) Committee.
[15] P. Mishra, et al., Descriptive statistics and normality tests for statistical data, Annals of Cardiac Anaesthesia 22 (1) (2019) 67–72.
[16] P.A. Shenga, et al., Simulation of Tropical Hardwood Processing – Sawing Methods, Log Positioning, and Outer Shape, BioResources 10 (4) (2015) 7640–7652.
[17] Franke, S. and J. Marto. *Investigation of Eucalyptus globulus wood for the use as an engineered material*. 2014. World Conference on Timber Engineering (WCTE).
[18] X. Li, et al., Rolling shear properties of cross-laminated timber (CLT) made from Australian Radiata Pine – An experimental study, Structures 33 (2021) 423–432.
[19] C.N. Filipescu, M.U. Stoehr, D.R. Pigott, Variation of lumber properties in genetically improved full-sib families of Douglas-fir in British Columbia, *Canada*. Forestry 91 (3) (2018) 320–326.
[20] R.J. McKimm, G. Waugh, R.L. Northway, Utilisation potential of plantation-grown eucalyptus nitens, Australian Forestry 51 (1) (1988) 63–71.
[21] H.M. McKenzie, et al., Processing young plantation-grown Eucalyptus nitens for solid-wood products. 2: Predicting product quality from tree, increment core, disc, and 1-M billet properties, N. Z. J. For. Sci. 33 (1) (2003) 79–113.
[22] H. Yoshihara, Measurement of the shear modulus of wood by static bending tests, Journal of Wood Science 44 (1) (1998) 15–20.
[23] S. Adamopoulos, M. Chavenetidou, C. Passialis, Span-to-depth ratio for shear free deformations in static bending of small wood specimens, Wood Research 56 (3) (2011) 429–434.
[24] Z.Q. Chen, et al., Estimating solid wood properties using Pilodyn and acoustic velocity on standing trees of Norway spruce, Annals of Forest Science 72 (4) (2015) 499–508.

Technical Report 1

NT016 / NIF080

Authors: Dr Marcus Noh

Dr Assaad Taoum

Prof Greg Nolan

NT016 / NIF080: Developing laminated structural elements from fibre-managed plantation hardwood

Contents

Introduction

This project aims to develop the grading, jointing and gluing expertise necessary for the production of structurally reliable glue-laminated elements using boards from a fibre-managed plantation hardwood resource. In this project, the feedstock recovered from unthinned and unpruned *Eucalyptus nitens* will be utilised for producing and testing of glulam samples.

Activity Summary

Since December 2020, activity has continued across each of the sub-programs with regular and active collaboration between CSAW and other researchers from School of Engineering at UTAS and Bern University of Applied Sciences in Switzerland.

Non-destructive evaluation of the MoE of the feedstock: The linear model that was determined in the previous stage to convert the AWV directly into the dynamic MoE of the 118 70-mm boards has been successfully employed to sort the plantation E. nitens feedstock for producing finger-jointed laminations into three quality groups: 37 boards to High, 42 to Medium and 39 to Low-quality group. The mean value and standard deviation of the evaluated dynamic MoE values of 118 boards are 13,042 MPa and 2,035 MPa, respectively. The dynamic MoE at the 33-percentile (11,677 MPa) and 66-percentile (13,602 MPa) of 118 samples were used as the upper limits for low- and medium-quality in sorting. The higher-quality lamellae were placed in the outer layers in 6 glulam elements (Refer to Appendix A for dynamic MoE values of all boards).

Means to efficiently and reliably finger joint the material into laminates for further assembly: The assessment of the feedstock in Switzerland was completed. The density and moisture content of the joining members were determined to segregate the finger joint samples into three groups based on the density, defects on the boards, location of the existing finger joint and the industrial jointing process.

Structural performance of the assembled glue-laminated beams: 6 full-size combined glulam samples were produced by industry and tested in the bending rig to investigate the sorting feedstock by the NDE method, load-bearing capacity and failure mode through bending. The dimension of the sample cross-section is 70x295mm2 and the 9 finger-jointed laminations were glued to form a beam. Figure 1 illustrates an elevation of the tested beams and Figure 2 shows the test setup of these beams.
Three different lay-up combinations were applied to evaluate the static MoE and MoR with different quality of the lamellae. The laminations of higher quality were placed in the outer 6 layers (three top and three bottom) and lower quality laminations used in the middle third. The grade and position combinations were:

- Medium/Low/Medium (MLM) – Samples GNC 1, 4 and 6
- High/Low/High (HLH) – Samples GNC 3 and 5
- High/Medium/High (HMH) – Sample GNC 2

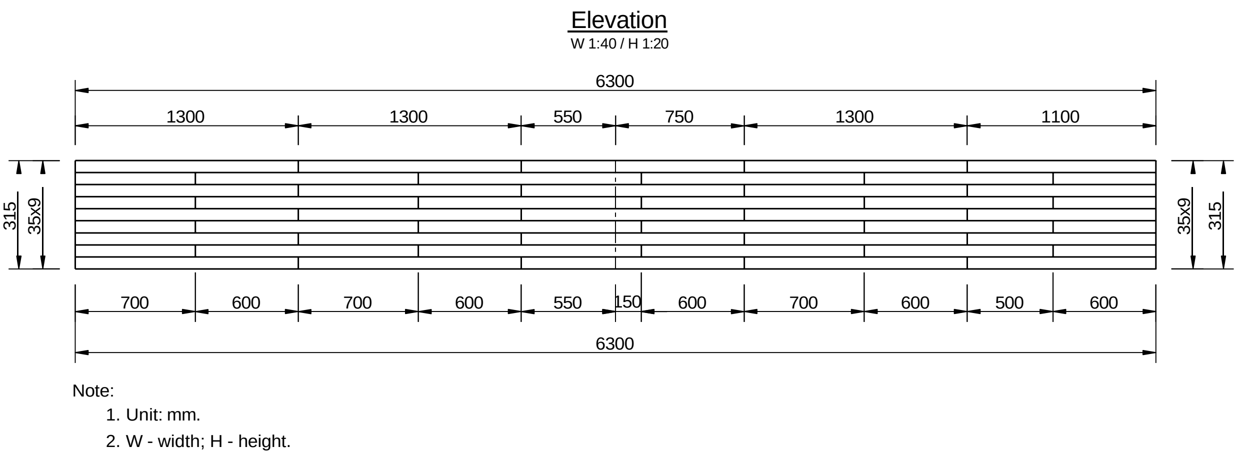


Figure 1: Elevation view of the tested beams

Figure 2: Bending test of a combined glulam sample

The static MoE of 6 glulam beams were determined and compared with the average dynamic MoE of the laminations in Top, Middle and Bottom position in the test rig. Figure 3 illustrates the MoE results of all 6 beams. Typical failure modes of the glulam samples are shown on Figure 4.

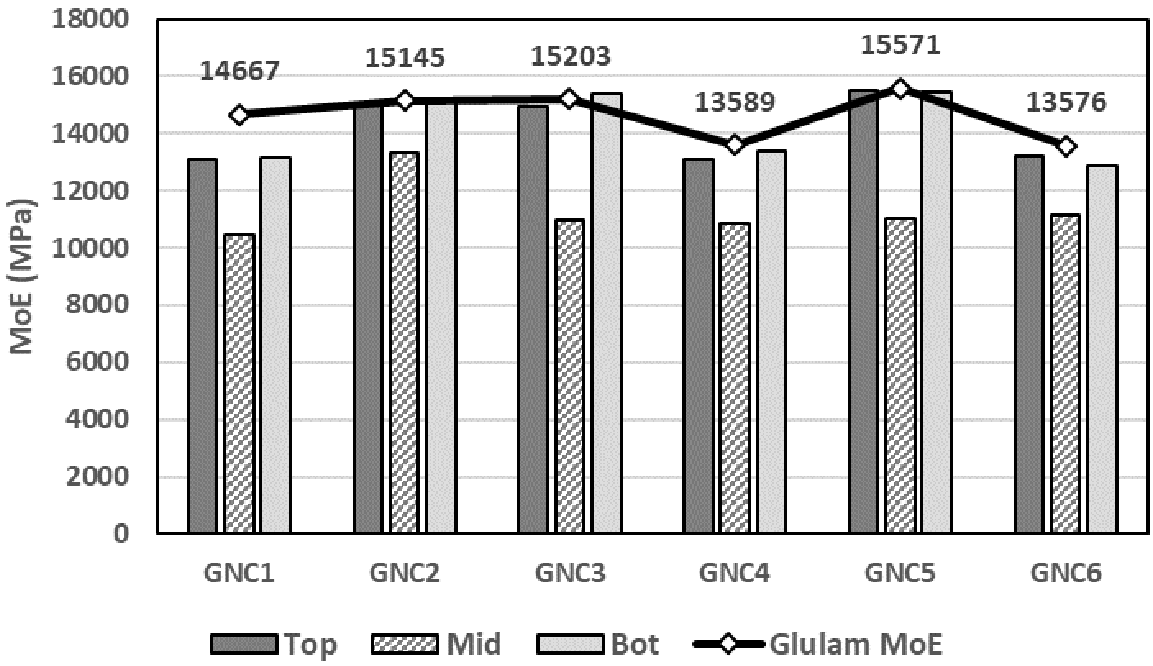


Figure 3: The result of 6 glulam elements and dynamic MoE of the laminations

As shown in Figure 3, it is apparent that the quality characterised by the average dynamic MoE value in the top and bottom layers are crucial in the global static MoE of the glulam element. On the other hand, the influence of the lower quality lamination in the middle third of the beam on the MoE of the glulam is marginal.

Figure 4: Failure mode of the glulam samples

This finding supports the assumption that the use of the low-quality E. nitnes feedstock in the region in the beam where lower stress occurs through bending is acceptable for producing reliable glulam elements.

The glulam samples with the high MoE laminations in the outer layers (GNC 2,3 and 5) show higher static MoE and MoR values than those with medium MoE boards as shown in Figure 5. All samples fell in GL13 (MoR>33 MPa, MoE>13,300 MPa) grade.

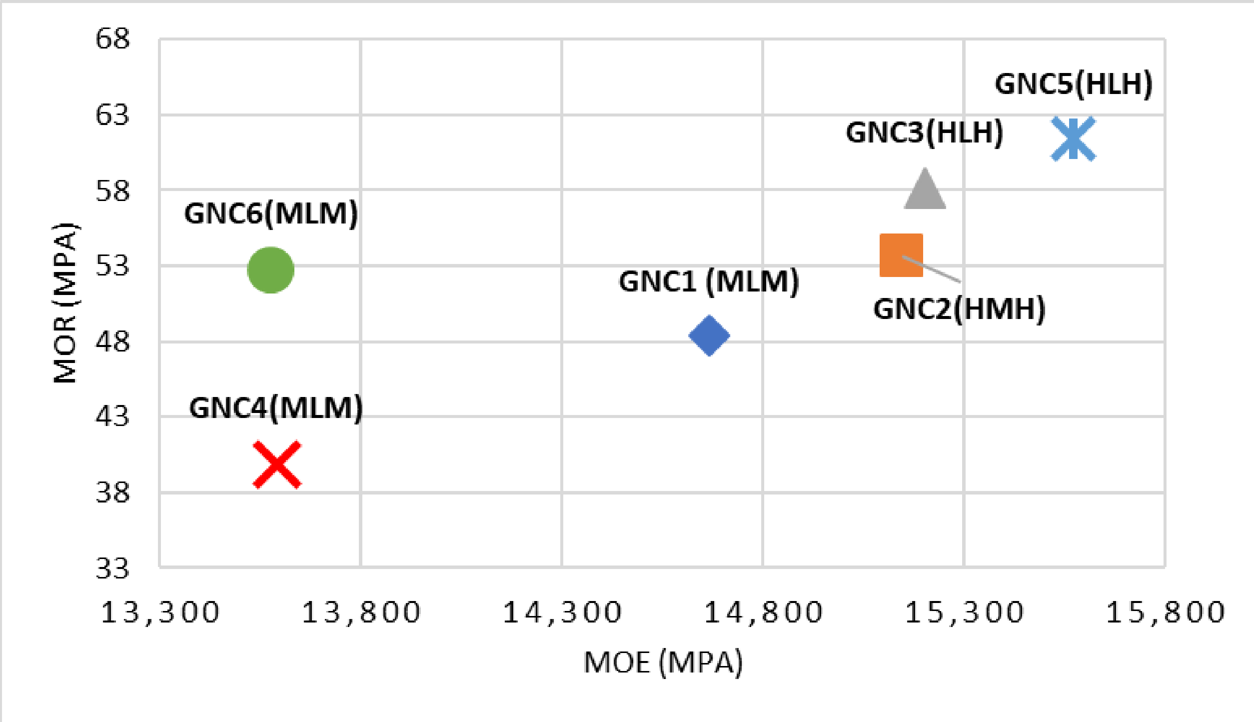


Figure 5 Static MoE and MoR of 6 glulam samples

Conclusions

1. The sorting of the plantation E. nitens feedstock using the linear model to convert the AWV to dynamic MoE (Dynamic MoE [MPa] = -20084 +6778.1 x AWV) was successfully employed in the production of the combined full-size glulam samples.

2. Three lay-up combinations for the 9-ply glulam beams (70x295x6000mm3) were used and all samples achieved GL 13 grade. The maximum and minimum static MoE value of the glulam was 15571 MPa and 13576 MPa, respectively. The maximum and minimum static MoR value were 39.85 MPa and 61.43 MPa, respectively.

3. Three out of six samples exhibited clean failure in the finger joints. These are GNC2, GNC4 and GNC5. Improving finger joint tensile strength could increase the bending performance of the glulam from plantation E. nitnes. Further finger joint test and delamination test are in progress and will provide a practice guide for the optimal finger joint production and face gluing.

Programmed Activities and Next Steps

During the last Steering Committee meeting (28/04/2021), it was established with industry partners that the target performance grade is GL13.

Grading: the newly acquired grading machine (Plessey) by CLTP can be used to grade feedstock for the next batch of glulam beams. UTAS will perform cross-checking of random boards for quality control purposes.

Gluing: Three out of six full-scale samples exhibited clean failure in the finger joints. Improving finger joint tensile strength could increase the bending performance of the glulam from plantation E. nitnes. In saying that, all six samples exhibited an MoR higher than GL13.

Test and performance: following the grading and gluing, UTAS will perform bending tests to identify the MoE, MoR and failure modes of the manufactured samples. UTAS can also use ISO/TR 19623 to provide a theoretical configuration of the beams before manufacturing in order to achieve the target strength grade.

Project timeline

COVID restrictions on travel and industry interactions complicate daily research activity and its efficiency for 6-8 months. Access to industry partner facilities in Tasmania for all but essential research personnel was significantly constrained for four months. In addition, delays is expected in the supply of new material to fabricate glulam samples in milestone 4 since reconditioning and dressing of the boards in the yard can be scheduled in Q2 or Q3 2021.

Appendix

Table A1 Dynamic MoE values of the finger jointed laminations in the glulam samples

MOE distribution

GNC1	1	2	3	4	5	Avg.
M	12,519	12,857	12,993	13,061	12,654	13,115
M	13,739	13,739	12,857	13,467	13,467	
M	13,196	12,722	12,519	13,061	13,874	
L	9,536	10,214	10,756	10,960	11,773	10,458
L	8,994	10,350	10,960	11,027	10,214	
L	10,756	11,909	8,316	10,417	10,688	
M	13,874	12,993	12,857	12,857	12,654	13,129
M	13,535	13,196	13,467	13,400	13,264	
M	13,535	12,519	12,519	12,857	13,400	

GNC2	1	2	3	4	5	Avg.
H	14,078	14,213	15,636	/	/	15,063
H	16,314	15,162	15,501	13,196	14,552	
H	15,365	15,298	17,534	14,552	14,416	
M	13,739	12,857	13,603	13,874	13,739	13,327
M	12,722	13,264	12,857	12,857	13,535	
M	13,874	13,739	12,315	13,196	13,739	
H	15,636	15,026	14,620	16,721	15,162	15,157
H	14,213	15,636	17,534	13,739	15,162	
H	14,620	14,620	13,942	15,365	15,365	

GNC3	1	2	3	4	5	Avg.
H	15,636	15,636	14,078	14,078	14,620	14,949
H	15,298	14,484	15,365	15,230	15,908	
H	/	14,484	14,484	14,484	15,501	
L	9,536	10,688	/	10,688	11,298	10,970
L	10,960	10,214	11,909	11,773	11,773	
L	11,773	10,688	9,536	11,773	/	
H	15,298	19,568	15,230	14,620	13,942	15,365
H	/	14,959	15,433	15,908	15,908	
H	15,298	14,484	14,755	14,484	15,230	

GNC4	1	2	3	4	5	Avg.
M	/	13,603	12,857	13,196	12,180	13,099
M	13,603	12,857	13,264	13,264	12,722	
M	13,739	13,467	12,315	12,722	13,603	
L	10,960	10,214	9,672	/	11,773	10,853
L	11,027	10,892	10,892	10,960	11,841	
L	9,807	8,858	10,892	13,264	10,892	
M	13,874	13,332	12,519	13,671	13,332	13,405
M	13,332	13,739	13,061	13,874	/	
M	13,603	12,993	12,857	13,603	13,874	

GNC5	1	2	3	4	5	Avg.
H	14,755	14,620	15,433	14,213	15,501	15,530
H	14,213	15,433	16,111	15,433	14,959	
H	16,382	18,212	16,721	15,433	/	
L	11,027	11,841	10,960	9,807	11,841	11,018
L	11,298	11,841	8,858	8,316	/	
L	14,484	11,909	10,417	10,824	10,824	
H	18,212	15,636	14,213	14,552	17,534	15,433
H	15,162	16,314	14,078	16,314	/	
H	14,552	14,416	15,501	15,026	14,552	

GNC6	1	2	3	4	5	Avg.
M	13,671	13,535	13,196	13,671	12,315	13,221
M	13,535	13,603	12,857	13,467	12,315	
M	13,739	13,467	12,857	12,857	/	
L	10,960	12,044	11,773	11,773	10,960	11,134
L	12,044	9,536	13,603	9,536	10,960	
L	10,892	10,214	10,688	10,892	/	
M	12,654	12,857	12,857	/	12,993	12,886
M	13,196	13,196	12,857	12,857	12,519	
M	12,722	13,739	12,654	12,654	12,654	

UNIVERSITY of TASMANIA

centre for sustainable architecture with wood
CSAW

NIFPI: Report on Australian and European standards for glulam with focus on hardwood and bonding

Albert Beeler, 21/6/2019

1. Table of contents

Contents

2. **Introduction**

This document provides a review and comparative analysis of the Australian and European standards regarding the glue and glue line of glue laminated (glulam) timber with a particular focus on glulam made from plantation Eucalyptus Nitens (E. Nitens). This review and comparison supports development of the research methodology and approach for the National Institute for Forest Products Innovation (NIFPI) project titled: 'Developing laminated structural elements from fibre-managed plantation hardwood'. What concerns the service classes, only classes 1 and 2 are investigated. The goal of the comparison is to identify the differences between the "Australian way" and the "European way" and whether project-relevant "holes" exist in the Australian standards. In other words, because the European standards cover more aspects and tests relating to glulam than the Australian standards, this document will outline which tests should be considered that are not necessarily required by the Australian standards for glulam, but which may increase the long term credibility and thus commercial potential of E.Nitens glulam products for domestic and international markets.
The standards reviewed and compared in this document are outlined in section 3. Each comparison is explicated partly using screenshots taken directly from the standards, and followed by a conclusion, which includes recommendations about how to proceed for the above mentioned NIFPI project. The recommendations are often distinguished between project phase 1 and 2, an approach which is explained further in section 4. The conclusions and recommendations for all the standards reviewed in this document are then summarised again in section 4.

In addition to glue and bonding tests, bending tests are also discussed in this document, because they are in some cases closely linked with bonding (e.g. tests for bending strength to test the finger joints) and because bending-test-equipment is available and ready to use at UTAS at Inveresk Campus.

Topics that are not included in this review and comparative analysis of Australian and European standards are as follows:

- CLT
- Glued solid timber
- Glulam with large finger joints
- Block glued glulam
- Nailed laminated timber
- Stress laminated timber
- Technical parameters (such as stress grading) apart from glue, bonding and bending tests
- Service class 3 according to AS 1328.1 (as only Service class 1 and 2 are envisaged for glulam in this project)

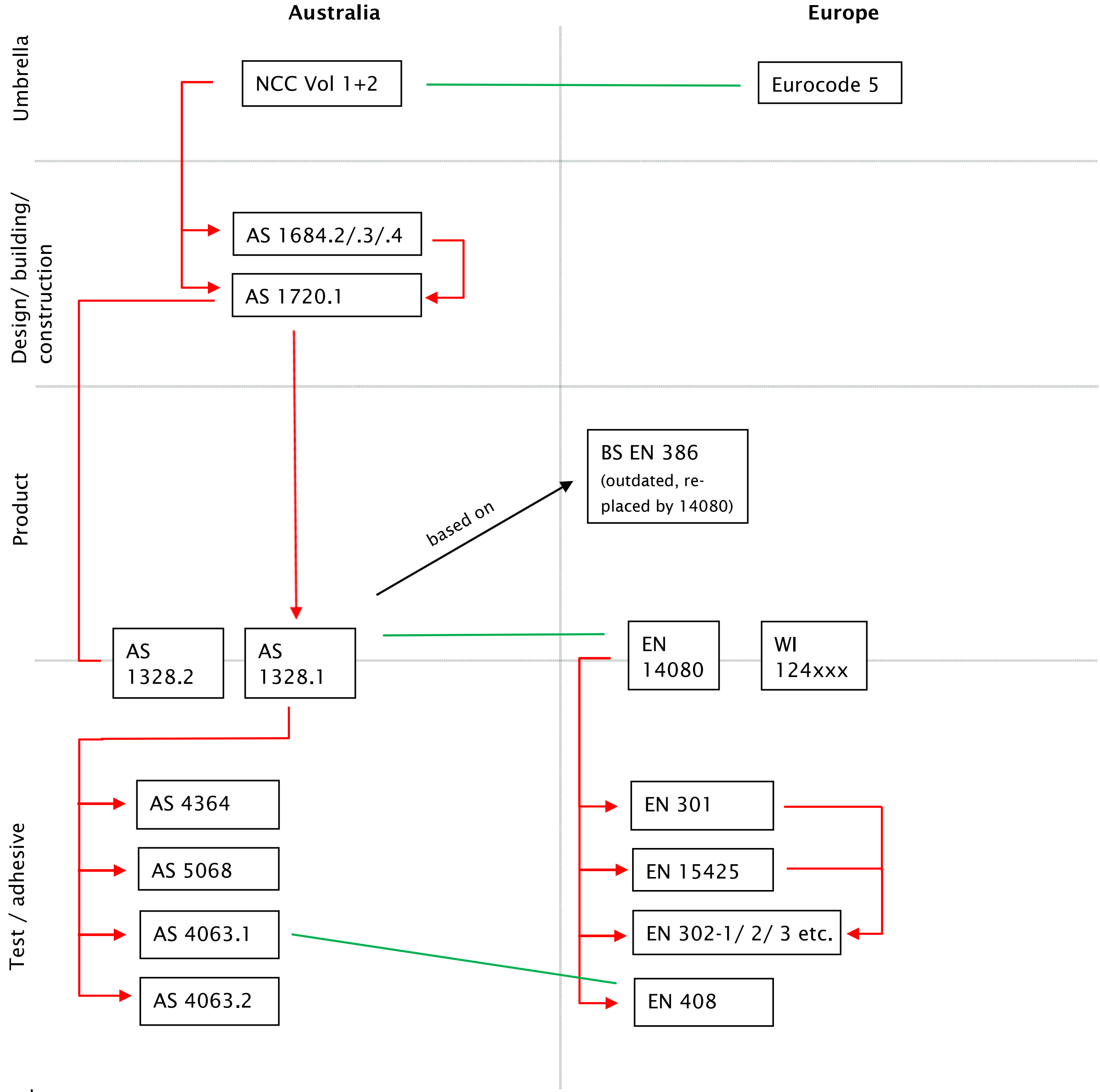
Regarding CLT it is important to note, that the basic tests in the standards concerning glue and glue line are the same as for glulam (Sigrist, 2019). For this reason, the topics glue and bonding for CLT are not investigated in this report. However, relevant considerations regarding CLT (e.g. cramping pressure limited because of use of vacuum press), will be mentioned.
If during the progression of the NIFPI project such topics gain in importance, then they should also be considered.

3. Standard description and findings

Key:

- Written in blue: Recommendations Albert Beeler. Of course, all these recommendations can be discussed and have to be adapted depending on the project progression.
- Recommendation equipment: Recommendations Albert Beeler regarding equipment (mainly about procurement or adaptation)

3.1 Overview about how the most important standards relate to each other



key:

- Red arrow: Compliance required (regarding glulam)
- Red line: Mentioned but no requirement for compliance
- Green line: Equivalent
- Black arrow: Meaning mentioned there

Note:

- *There are more standards referred to regarding adhesive, bonding and bending tests for glulam than in this overview; here only the most important ones are shown and of them again only the most important ones for the project are explained in this document.*
- *Some standards are at the same time product standards (define the product requirements for glulam) and also test standards (describe in detail test methods). This is the case e.g. for AS 1328.1 and EN 14080.*

Standards mentioned in the overview (for more details see reference list):

NCC vol. 1 and 2, May 2019 (definitive version)

AS 1684.2 — 2010: Residential timber-framed construction - Part 2: Non-Cyclonic Areas
AS 1684.3 — 2010: Residential timber-framed construction - Part 3: Cyclonic Areas
AS 1684.4 — 2010: Residential timber-framed construction - Part 4: Simplified—Non-Cyclonic Areas

AS 1720.1–2010 Timber structures - Part 1: Design methods
AS 1720.2–2006 Timber structures - Part 2: Timber properties

AS/NZS 1328.1:1998: Glued laminated structural timber Part 1: Performance requirements and minimum production requirements

AS/NZS 1328.2:1998: Glued laminated structural timber Part 2: Guidelines for AS/NZS 1328: Part 1 for the selection, production and installation of glued laminated structural timber

AS/NZS 4063.1:2010: Characterization of structural timber Part 1: Test methods

AS/NZS 4063.2:2010: Characterization of structural timber Part 2: Determination of characteristic values

AS/NZS 4364:2010: Timber—Bond performance of structural adhesives

AS 5068—2006 (reconfirmed 2016): Timber—Finger joints in structural products—Production requirements

BS EN 386:1995: Glued laminated timber—Performance requirements and minimum production requirements

EN 301:2017 (D): *Title in English:* Adhesives, phenolic and aminoplastic, for load-bearing timber structures - Classification and performance requirements

EN 302-1:2013: Adhesives for load-bearing timber structures. Test methods. Determination of longitudinal tensile shear strength

EN 302-2:2017: Adhesives for load-bearing timber structures – Test methods - Part 2: Determination of resistance to delamination

EN 302-3:2017*:* Adhesives for load-bearing timber structures – Test methods - Part 3: Determination of the effect of acid damage to wood fibres by temperature and humidity cycling on the transverse tensile strength

EN 408:2010+A1:2012 (E): *Title in English:* Timber structures - Structural timber and glued laminated timber - Determination of some physical and mechanical properties

EN 15425:2017 (D): *Title in English:* Adhesives - One component polyurethane (PUR) for load-bearing timber structures - Classification and performance requirements

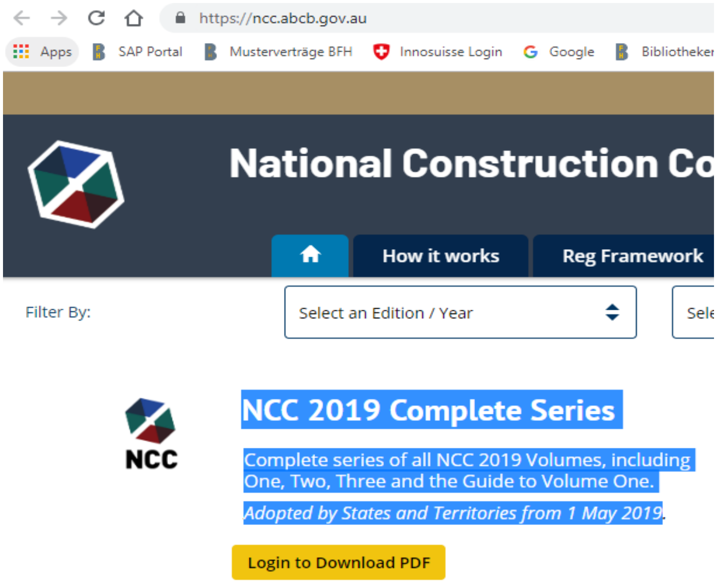
FprEN 14080:2013 (E) (FINAL DRAFT): Timber structures - Glued laminated timber and glued solid timber – Requirements

WI 124xxx:2018 (IN PROGRESS!): Timber structures — Hardwood glued laminated timber — Requirements

3.2 NCC

3.2.1 Conditions

- Skimmed over vol 1 (and its guide) and vol 2 and looked with the search function for keywords such as «glulam», «glue-lam», «CLT»
- These are the documents referred to:



- Only vol 1 and 2 were considered because they are the only relevant ones for the construction of buildings

Contents and Introduction

Introduction to the National Construction Code (NCC)

About the NCC

The NCC is Australia's primary set of technical design and construction provisions for buildings. As a performance-based code, it sets the minimum required level for the safety, health, amenity, accessibility and sustainability of certain buildings. It primarily applies to the design and construction of new buildings, and plumbing and drainage systems in new and existing buildings. In some cases it may also apply to structures associated with buildings and new building work or new plumbing and drainage work in existing buildings.

The Australian Building Codes Board (ABCB), on behalf of the Australian Government and each State and Territory government, produces and maintains the NCC. When determining the content of the NCC, the ABCB seeks to—

- ensure requirements have a rigorously tested rationale; and
- effectively and proportionally address applicable issues; and
- create benefits to society that outweigh costs; and
- consider non-regulatory alternatives; and
- consider the competitive effects of regulation; and
- not be unnecessarily restrictive.

The primary users of the NCC include architects, builders, plumbers, building surveyors, hydraulic consultants, engineers and other building and plumbing related professions and trades.

Format of the NCC

The NCC is published in three volumes. The Building Code of Australia (BCA) is Volumes One and Two of the NCC and the Plumbing Code of Australia (PCA) is Volume Three of the NCC.

Components of the NCC

The NCC provides the technical provisions for the design and construction of buildings and other structures, and plumbing and drainage systems.

NCC Volume One primarily covers the design and construction of multi-residential, commercial, industrial and public assembly buildings and some associated structures.

NCC Volume Two primarily covers the design and construction of smaller scale buildings including houses, small sheds, carports and some associated structures.

NCC Volume Three covers the design, construction and maintenance of plumbing and drainage systems in new and existing buildings.

- Termites and related requirements not considered
- Fire resistance not considered
- State-relevant requirements (for instance durability Queensland, see marked in blue) not considered:

NCC 2019 Building Code of Australia - Volume Two Page 159

Framing

Part 3.4.3 Timber framing

Appropriate *Performance Requirements*

Where an alternative timber framing design is proposed as a *Performance Solution* to that described in Part 3.4.3, that proposal must comply with—

(a) *Performance Requirement* P2.1.1; and

(b) the relevant *Performance Requirements* determined in accordance with A2.2(3) and A2.4(3) as applicable.

Acceptable Construction Manuals

3.4.3.0

Performance Requirement P2.1.1 is satisfied for a timber frame if it is designed and constructed in accordance with the following, as appropriate:

(a) Design of timber structures: AS 1720.1.

(b) Design of nailplated timber roof trusses: AS 1720.5.

(c) Residential timber-framed construction – non-cyclonic areas: AS 1684.2.

(d) Residential timber-framed construction – cyclonic areas: AS 1684.3.

(e) Residential timber-framed construction – non-cyclonic areas (simplified): AS 1684.4.

(f) Installation of particleboard flooring: AS 1860.2.

State and Territory Variations

In Queensland after 3.4.3.0(f) insert Qld 3.4.3.0(g) as follows:

Qld 3.4.3.0(g) Timber Species

(g) Timber Species

In addition to sub-clauses (a) to (f) above, timber used for structural purposes must be a species scheduled for the appropriate use in Schedules A, B or C of Book 2 of the December 2017 version of the "Queensland Government, Department of Agriculture, Fisheries and Forestry - Construction timbers in Queensland, Book 1 and Book 2: Properties and specifications for satisfactory performance of construction timbers in Queensland - Class 1 and 10 buildings (Houses, carports, garages, greenhouses and sheds)".

3.2.2 Vol 1 – Relevant findings

- Good overview about which building types are covered (marked in blue):

NCC 2019 Building Code of Australia - Volume One Page 10

Contents and Introduction

Introduction to NCC Volume One

About NCC Volume One

NCC Volume One contains technical design and construction requirements for all Class 2 to 9 buildings (multi-residential, commercial, industrial, and public assembly buildings) and their associated structures.

NCC Volume One contains the requirements for—

- all Class 2 to 9 buildings; and
- access requirements for people with a disability in Class 1b and 10a buildings; and
- certain Class 10b structures including access requirements for people with a disability in Class 10b *swimming pools*.

- Reference to the relevant standards for timber construction (marked in blue):

B1.4 Determination of structural resistance of materials and forms of construction

The structural resistance of materials and forms of construction must be determined in accordance with the following, as appropriate:

(a) Masonry (including masonry-veneer, unreinforced masonry and reinforced masonry): AS 3700, except—

(i) '(for piers—isolated or engaged)' is removed from Clause 8.5.1(d); and

(ii) where Clause 8.5.1 requires design as for unreinforced masonry in accordance with Section 7, the member must also be designed as unreinforced masonry in accordance with Tables 10.3 and 4.1(a)(i)(C) of AS 3700.

(b) Concrete:

(i) Concrete construction (including reinforced and prestressed concrete): AS 3600.

(ii) Autoclaved aerated concrete: AS 5146.1.

NCC 2019 Building Code of Australia - Volume One Page 52

B1.4

Structure

Deemed-to-Satisfy Provisions

(iii) Post-installed and cast-in fastenings: AS 5216.

(c) Steel construction:

(i) Steel structures: AS 4100.

(ii) Cold-formed steel structures: AS/NZS 4600.

(iii) Residential and low-rise steel framing: NASH Standard – Residential and Low-Rise Steel Framing Part 1 or Part 2.

(d) Composite steel and concrete: AS/NZS 2327.

(e) Aluminium construction: AS/NZS 1664.1 or AS/NZS 1664.2.

(f) Timber construction:

(i) Design of timber structures: AS 1720.1.

(ii) * * * * *

(iii) Timber structures: AS 1684.2, AS 1684.3 or AS 1684.4.

(iv) Nailplated timber roof trusses: AS 1720.5.

3.2.3 Guide about Vol 1 – Relevant information

No relevant information found

3.2.4 Vol 2 – Relevant information

- Relevant standards for timber constructions (marked in blue):

NCC 2019 Building Code of Australia - Volume Two Page 159

Framing

Part 3.4.3 Timber framing

Appropriate *Performance Requirements*

Where an alternative timber framing design is proposed as a *Performance Solution* to that described in Part 3.4.3, that proposal must comply with—

(a) *Performance Requirement* P2.1.1; and

(b) the relevant *Performance Requirements* determined in accordance with A2.2(3) and A2.4(3) as applicable.

Acceptable Construction Manuals

3.4.3.0

Performance Requirement P2.1.1 is satisfied for a timber frame if it is designed and constructed in accordance with the following, as appropriate:

(a) Design of timber structures: AS 1720.1.

(b) Design of nailplated timber roof trusses: AS 1720.5.

(c) Residential timber-framed construction – non-cyclonic areas: AS 1684.2.

(d) Residential timber-framed construction – cyclonic areas: AS 1684.3.

(e) Residential timber-framed construction – non-cyclonic areas (simplified): AS 1684.4.

(f) Installation of particleboard flooring: AS 1860.2.

- Good overview which building types are covered (marked in blue):

NCC 2019 Building Code of Australia - Volume Two Page 9

Contents and Introduction

Introduction to NCC Volume Two

About NCC Volume Two

NCC Volume Two contains technical design and construction requirements for certain residential and non-habitable buildings and structures.

Volume Two contains the requirements for—

- Class 1 and 10a buildings (other than access requirements for people with a disability in Class 1b and 10a buildings); and
- certain Class 10b structures (other than access requirements for people with a disability in Class 10b *swimming pools*); and
- Class 10c *private bushfire shelters*.

3.2.5 Conclusion NCC (all parts)

The relevant standards for timber structures are

- AS 1720.1
- 1684.2
- 1684.3 or 1684.4

3.3 **AS 1720.1 – 2010: Timber structures Part 1: Design methods**

3.3.1 Conditions

- Skimmed over the document and also looked with the search function for the terms «glulam», «glue-lam», «CLT», «species», «hardwood», «softwood» and «plantation». The four last ones were chosen to see whether there are information or not about which wood species are covered with the standard and if there are any restrictions regarding hardwood or plantation wood.
- Also, the two Amendment No.1 and 2 to 1720.1—2010 were considered.

3.3.2 Relevant findings

- Very much about structural aspects of buildings
- No information about CLT
- No explicit information about which wood species are covered and which not. But often, softwoods and hardwoods are mentioned and sometimes eucalyptus → no limitations regarding (plantation) hardwood found
- Glulam: AS 1328.1 is relevant

93 **AS 1720.1—2010**

SECTION 7 GLUED-LAMINATED TIMBER CONSTRUCTION

7.1 GENERAL

This Section shall be applied in conjunction with Sections 2 and 3. The provisions of this Section apply specifically to glued-laminated timber members manufactured in accordance with AS/NZS 1328.1.

Additional design methods, including methods for taper-cut and curved beams, are contained in Appendix E.

Where any glued-laminated timber is likely to be exposed to water or to damp conditions, the glued laminated timber shall be bonded with Type 1 adhesive specified in accordance with AS/NZS 1328.1.

- Note: Various information on roughly 40 timber species commonly used in Australia are given in AS/NZS 1720.2:

153 **AS 1720.1—2010**

APPENDIX G

MISCELLANEOUS DESIGN INFORMATION

(Informative)

G1 ADDITIONAL INFORMATION

Basic design properties and additional design information on roughly 40 species commonly used in Australia are given in AS/NZS 1720.2.

3.3.3 Conclusion

- For glulam, AS 1328.1 is relevant

3.4 ASAS 1684 (Niveau: Design und Planung)

3.4.1 Conditions/ explanation

- This standard consists of four parts (see AS 1684.1-1999, page 3):
  AS 1684 Residential timber-framed construction
  AS 1684.1 Part 1: Design criteria
  AS 1684.2 Part 2: Non-cyclonic area
  AS 1684.3 Part 3: Cyclonic area
  AS 1684.2 Part 4: Simplified-Non-cyclonic area.
- Skimmed over these documents apart from part one as it is not relevant for us (see above). Further, with the search function it was looked for the terms «glulam», «glue-lam», «CLT», «species», «hardwood», «softwood» and «plantation». The last four terms were chosen to see whether there are information or not about which wood species are covered with the standard and if there are any restrictions regarding hardwood or plantation wood.
- The numerous supplements regarding wind classification were not considered.

3.4.2 Relevant findings

- Very much about structural aspects of buildings and applications, such as flooring joists etc.
- No explicit information about which wood species is covered and which not. But often, softwoods and hardwoods are mentioned and sometimes eucalyptus → no limitations regarding (plantation) hardwood found
- The only information found about which standard is relevant for glulam: AS 1720.1. Hence, finally AS 1328.1 is relevant as seen in the explanation for AS 1720.1.

AS 1684.2—2010 16

TABLE 1.2

STRESS GRADES

Species or species group	Most common stress grades available	Other stress grades available
Cypress (unseasoned)	F5	F7
Hardwood (unseasoned)	F8, F11, F14	F17
Hardwood (seasoned)	F17	F22, F27
Hardwood (seasoned Western Australia)	F14	—
Seasoned softwood (radiata, slash, hoop, Caribbean, pinaster pines, etc.)	F5, F7, F8, MGP10, MGP12	F4, F11, MGP15
Douglas fir (Oregon) (unseasoned)	F5, F7	F8*, F11*
Spruce pine fir (SPF) (seasoned)	F5	F8
Hemfir (seasoned)	F5	F8

* Span tables in Supplements for unseasoned hardwood F8 and F11 may be used for unseasoned F8 and F11 softwood as well.

NOTES:

1 Timber that has been visually, mechanically or proof stress graded may be used in accordance with this Standard at the stress grade branded thereon.

2 Check local timber suppliers regarding availability of timber stress grades.

1.12 ENGINEERED TIMBER PRODUCTS AND ENGINEERED WOOD PRODUCTS (EWPs)

Fabricated components (e.g., roof trusses, glued-laminated timber members, I-beams, laminated veneer lumber, laminated strand lumber and nailplate-joined timber) may be used where their design is in accordance with AS 1720.1 and their manufacture and use complies with the relevant Australian Standards.

Glued-laminated timber, I-beams, laminated veneer lumber (LVL) and laminated strand lumber (LSL) are also commonly referred to as EWPs (engineered wood products).

- No specific information about CLT found. Only information about non-standardised EWPs (interesting regarding CLT as there is no Australian standard for this product):

2 In some situations, there are no relevant Australian Standards applicable to the design, manufacture or use of engineered timber products. In such cases, the use of these products in accordance with this Standard is subject to the approval of the regulatory authority and the recommendations of the specific manufacturer, who may require provisions additional to those contained in this Standard. These may include, but are not restricted to, additional support, lateral restraint, blocking, and similar provisions.

1.13 SIZE TOLERANCES

When using the Span Tables given in the Supplements, the following maximum undersize tolerances on timber sizes shall be permitted:

(a) *Unseasoned timber:*

(i) *Up to and including F7* .... 4 mm.

(ii) *F8 and above* .... 3 mm.

(b) *Seasoned timber—All stress grades* .... 0 mm.

NOTE: When checking unseasoned timber dimensions onsite, allowance should be made for shrinkage, which may have occurred since milling.

dards Australia www.standards.org.au

17 **AS 1684.2—2010**

3.4.3 Conclusion

Glulam: AS 1720.1 is relevant and therefore AS 1328.1

3.5 **AS 1328.1 – 1998: Glued laminated structural timber - Performance requirements and minimum production requirements**

3.5.1 Conditions

- Read the whole standard in detail

3.5.2 Relevant findings

- AS 1328 is based on BS EN 385:1995, which is outdated and was replaced by EN 14080 (which is THE European standard for glulam), which is explained below
- PUR glue nowhere mentioned
- Nowhere mentioned which timber species (hardwood, softwood, precise species, plantation timber) are covered by this standard → no restrictions for plantation E. Nitens.
- Requirements for the glue itself is given in AS/NZS 4364 (note: it's chiefly relevant for the glue producers)

AS/NZS 1328.1:1998 2

PREFACE

This Australian/New Zealand joint Standard was prepared by Joint Technical Committee TM/4 Glued timber products. It is based on performance based BS EN 386:1995 *Glued laminated timber—Performance requirements and minimum production requirements* which has been amended only where necessary to comply with Australian and New Zealand requirements. It supersedes AS 1328—1987 and NZS 3606:1987.

This Standard incorporates Amendment No. 1 (March 2011). The changes required by the Amendment are indicated in the text by a marginal bar and amendment number against the clause, note, table, figure or part thereof affected.

Glued laminated timber is obtained by bonding together a number of laminations having their grain essentially parallel. In this way a member with a rectangular solid cross section can be produced.

The requirements cover timber quality, the strength of end-joints and face-joints between laminations, and adhesive type which is related to Service Classes 1, 2 and 3. Service Class 3 requires weather resistant adhesives and may also require preservative treated timber. The requirements for the adhesives are given in AS/NZS 4364.

- Definition service classes 1 – 3 (Note: in this project, we aim to achieve Service Class 1 and 2)

1.3.10 Service Class 1

Service Class characterized by a moisture content in the materials corresponding to a temperature of 20°C and relative humidity of the surrounding air only exceeding 65% for a few weeks per year. (See Appendix A).

NOTE: In Service Class 1 the average equilibrium moisture content in most glulam will not exceed 12%.

1.3.11 Service Class 2

Service Class characterized by a moisture content in the materials corresponding to a temperature of 20°C and relative humidity of the surrounding air only exceeding 85% for a few weeks per year. (See Appendix A).

NOTE: In Service Class 2 the average equilibrium moisture content in most softwoods will not exceed 20%.

1.3.12 Service Class 3

Service Class characterized by climatic conditions leading to higher moisture contents than Service Class 2, or where timber is directly exposed to sun and/or rain. (See Appendix A).

1.3.13 Specimen

test specimen of glulam of rectangular shape.

1.3.14 Test bar

test specimen of rectangular right-angled prismatic form.

7 AS/NZS 1328.1:1998

- Initial qualification test of completed glulam: Either by testing of a **300mm** deep glulam (method 1 below) or by calculating the bending strength f'b (method 2 below). As the focus of this report is on gluing and adhesive, the mentioned characteristic strengths (as tension and shear) are not further discussed. An exception though is bending strength and modulus of elasticity in bending: This is discussed in the conclusion of this standard as it is in the context with the bending-test machine at our Inveresk Campus.

2.4.3 Initial qualification tests

Qualification tests shall be undertaken whenever a new process or process change involving, for example, a new adhesive/species combination, finger joint profile, lamination thickness or similar. Initial qualification tests shall be carried out either by Method 1 of Clause 2.4.3.1 or Method 2 of Clause 2.4.3.2.

2.4.3.1 *Method 1*

Determination from tests on completed glulam The characteristic strength of a glulam member in bending compression, tension and shear and characteristic modulus of elasticity in bending, shall be determined by undertaking tests on completed 300 mm deep glulam members in accordance with the AS/NZS 4063 series.

see p. 5: standard title:
Characterization of structural timber (all Parts)

2.4.3.2 *Method 2*

Determination from lamination properties The following shall apply:

(a) The characteristic strengths of a 300 mm deep horizontally laminated glulam member in bending and tension shall be computed using equations 1 and 2.

$$f'_b = 0.75\,(1 + 0.05\,S_{min})\; f'_{b,ej} \leq f'_{b,stock} \qquad \ldots (1)$$

$$f'_t = 0.75\,(1 + 0.05\,S_{min})\; f'_{t,ej} \leq f'_{t,stock} \qquad \ldots (2)$$

where

$f'_{b,ej}$ = characteristic bending strength of the finger joints in flatwise bending determined in accordance with AS 5068

$f'_{b,stock}$ = characteristic bending strength of the selected grade of lamination stock

$f'_{t,ej}$ = characteristic tension strength of the finger joints determined in accordance with AS 5068

$f'_{t,stock}$ = characteristic tension strength of lamination stock of the selected grade of the lamination stock

S_{min} = minimum spacing of end joints (m)

(b) The modulus of elasticity shall be determined by bending of lamination stock about the minor axis in accordance with the provisions of the AS/NZS 4063 series. The characteristic value of the modulus of elasticity so determined shall be deemed to apply to the laminations within the glued laminated member. The effective stiffness properties shall be determined using composite beam theory.

(c) Where manufacturers use timber, graded in accordance with the relevant grading standard for which in-grade test data are available, the values of $f'_{s,stock}$, $f'_{c,stock}$ and E_{stock} may be deemed to apply.

- the two testing types have to be distinguished:
  a) (Initial) Qualification test
  b) Daily quality control test (=Routine test)

  Regarding differentiation between these two types about adhesives, the following table gives a good overview:

TABLE 2.1

QUALIFICATION AND ROUTINE TEST PROCEDURES

Service	**Class 1**		**Class 2**		**Class 3**
Qualification test	**Type I adhesive**	**Type II adhesive**	**Type I adhesive**	**Type II adhesive**	**Type I adhesive only**
	Delamination test method A Appendix C	Delamination test method C Appendix C	Delamination test method A Appendix C	Delamination test method C Appendix C	Delamination test method A Appendix C
Routine tests	**Type I and Type II adhesives**		**Type I and Type II adhesives**		**Type I adhesives only**
	Delamination test method C Appendix C OR Block shear Appendix D OR Dry cleavage Appendix B		Delamination test method C Appendix C OR Block shear Appendix D OR Dry & wet cleavage Appendix B		Delamination test method A or method B Appendix C OR Dry and wet cleavage Appendix B

NOTE: Where dry and wet cleavage is performed two full cross sections are required.

2.6.4 Acceptance criteria for delamination tests

Depending on the method and number of cycles the total delamination percentage of each cross-sectional specimen shall be less than the values given in Table 2.2.

TABLE 2.2

MAXIMUM VALUES FOR THE TOTAL DELAMINATION PERCENTAGES

Method	**Applicable to adhesive type**	**Max. percentage after cycle No:**		
		1	**2**	**3**
A	Type I	—	5	10
B	Type I	4	8	—
C	Type II	10	—	—

- Specimen number and frequency depends on whether it is an initial or routine test:
  New:

AS/NZS 1328.1:1998 10

2.6 GLUELINE INTEGRITY

2.6.1 General

The requirements for glueline integrity shall be based on testing of the glueline in a full cross-sectional specimen, which shall be cut from the manufactured glulam member. The specimens shall be representative of the production. The test requirements are summarized in Table 2.1.

2.6.2 Qualification tests

Qualification tests shall be undertaken whenever a new process or process change such as a new adhesive/species combination is introduced.

For members of Service Classes 1 and 2 the testing shall be delamination tests in conformity with method A of Appendix C.

For members of Service Class 3 delamination tests shall be made in conformity with method A of Appendix C.

For each species, adhesive, treatment or process combination, a minimum of 5 full cross-sections shall be tested and shall meet the requirements of 2.6.4 or 2.6.5.

2.6.3 Routine tests

For structures of Service Class 1 the testing shall be either by delamination tests method C of Appendix C, or block shear of Appendix D, or dry cleavage of Appendix B.

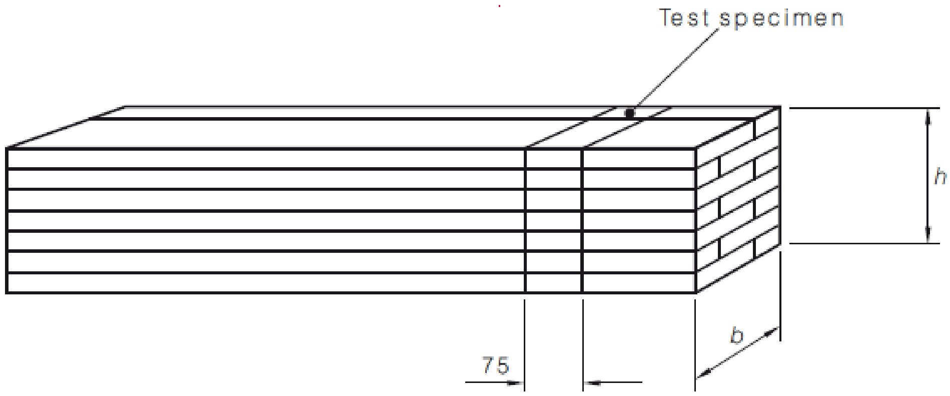
For structures of Service Class 2 the testing shall be either by delamination test method C of Appendix C or block shear of Appendix D, or dry and wet cleavage of Appendix B.

For structures of Service Class 3 the testing shall be either by delamination test method A or B of Appendix C, or dry and wet cleavage of Appendix B.

For each shift in which gluing is carried out, one full cross-sectional specimen shall be tested for each press load or every 10 m^3 of production.

- The different mentioned delamination tests A, B and C are all similar (apply a partial vacuum and after overpressure and drying of the wood in varied conditions). They differ in terms of time, pressure, drying conditions, number of cycles, see table 2.2. The sample size is always the same (see figure C1) and the samples are cut out of the glulam produced (so no separate sample making and gluing is needed). Furthermore, they are very similar to the 3 delamination methods in EN 14080 Annex C.

AS/NZS 1328.1:1998 26



Size in millimetres

FIGURE C1 TEST SPECIMEN CUT FROM A GLULAM MEMBER

- Shear test: Small samples, tested in dry condition (20˚C, 65% relative humidity) parallel to the grain. The samples are cut out of the glulam produced (so no separate sample making and gluing are needed). Test very similar to the one in EN 14080 Annex D.
- Finger joints: Must be manufactured according to AS 5068 (first screenshot below) and for Factory production control FPC (Internal control), they must be tested either with sample testing or proof testing (second screenshot below)
- Face joint testing FPC: The frequency is given in 4.1.4 (second screenshot below)

2.5 END JOINTS

A1 Finger joints shall be manufactured and tested in accordance with AS 5068. End joints other than finger joints, eg, scarf joints, shall be tested in accordance with the provisions of AS 5068. The alternative end joint shall be treated as a substitute finger joint in interpreting AS 5068. In all such specimens the end joint shall be representative of the normal production method. Where the end joints are cured with the face joints in normal production, the test specimens shall be prepared by an identical method by forming a blank billet. In a blank billet, a glulam member shall be constructed without face joint adhesive so as to provide sufficient (at least 30 for qualification and 3 per shift for routine tests) end joint test specimens. Where such joints are pre-cured they shall be taken directly after the pre-cure operation.

AS/NZS 1328.1:1998 10

4.1.3 End joints

End joint quality shall be verified by the testing of sample joints or by proof testing.

4.1.3.1 *Verification by sample testing*

The strength of end joints in laminations shall be verified by testing in flatwise bending in accordance with the provisions of AS 5068. For the purpose of checking finger joint strength to AS 5068, the declared characteristic strength in flatwise bending shall be given by:

$$f'_{\mathrm{b,ej}} = \frac{1.33\, f'_{\mathrm{b}}}{(1 + 0.05\, S_{\mathrm{min}})}$$

2.4.3.1 is an initial qualification test on a gluelam sample, not only on a lamination

NOTE: If f'_{b} has been determined by Method 1 of Clause 2.4.3.1 then it may be advantageous to determine $f'_{\mathrm{b,ej}}$ by flatwise bending tests on end joints in laminations to the AS/NZS 4063 series.

4.1.3.2 *Verification by proof testing*

End joints may be verified by proof testing of laminations in accordance with the following principles:

(a) In beams, the proof testing need only apply to the outer laminations, but for tension members, all laminations shall be proof tested.

(b) The proof load shall apply a stress in bending or tension equal to $f'_{\mathrm{b,pt}}$ or $f'_{\mathrm{t,pt}}$ as applicable. If proof testing takes place before the joints have been fully cured, then the proof testing may be reduced by an amount established by appropriate tests.

4.1.4 Face joints

The face joint gluelines shall be tested in a full cross-sectional specimen, which is to be cut from a cured glulam member produced during each working shift. For each shift in which gluing is carried out, one full cross-sectional specimen shall be taken for every press load or every 10 m^3 of production, whichever is the greater.

If all tests for a 3 month period satisfy the requirements, the number of samples may be reduced to not less than half the number prescribed above, with a minimum of one test per day.

The results of the testing for glueline integrity shall be documented as described in Appendix B, Appendix C and Appendix D for cleavage, delamination and block shear respectively.

3.5.3 Conclusion

- Based on BS EN 385:1995, which is outdated and was replaced by EN 14080 (which is THE European standard for glulam)
- Probably because it is based on an outdated standard, PUR adhesive is nowhere mentioned in AS 1328.1
- No restriction regarding wood species: Hence planation E. Nitens is covered
- Initial qualification test of completed glulam: Can be done by testing of a **300mm** deep glulam. MOR and MOE therefore possible to test in Inveresk. However, from a practical standpoint of view and in view of the European standard (see EN 14080 below), it would be better to test deeper beams, eg.50mm (and therefore min. span acc. to the European standard 15d = 15 x 450mm = 6750mm). If it doesn't cost too much, the test machine in Inveresk should be adapted for that. Note: If such adaptions are not possible at Inveresk, big beams could be tested in Biel.
- Requirements for the glue (the glue itself, not to be confused with its performance in the glulam): AS 4364 is relevant (note: It is chiefly relevant for the glue producers), see below in the description of AS 4364.

- Regarding face bonding: To be tested in the first project phase: Block shear and delamination. It has to be discussed which test method shall be used (if the Australian (AS 1328.1) or European one (EN 14080) or both). Cleavage shall not be tested as not relevant for European standards and would make a further test method necessary besides shear und delamination testing. Recommendation equipment: Procurement of an autoclave or another device that allows delamination tests (partial vacuum and over pressure)
- Finger joints
  - Either sample testing or proof testing
  - Sample testing: Has to be tested on bending
  - Proof testing: Bending OR tension tests (the same is also said in AS 5068, see there). In the first phase, only bending tests shall be carried out as UTAS has all the necessary equipment for that. In the second phase, it makes probably sense to test also on tension to gain more knowledge about the finger joints. If this will not be possible at UTAS, tension tests are possible in Biel. Again, it has to be discussed if the tests shall be done according to the Australian or European standards.
  - To be manufactured and tested according to AS 5068 (AS 5068 described below)

3.6 AS 5068 – 2006 (reconfirmed in 2016): Timber—Finger joints in structural products—Production requirements

3.6.1 Conditions

- Read the whole standard in detail including amendments

3.6.2 Relevant findings

- No information about CLT
- For bending and tension test, the specimen length is not important (exception: Bending test length > 12d)
- Softwood and hardwood covered:

AS 5068—2006 2

PREFACE

This Australian/New Zealand Joint Standard was prepared by Joint Technical Committee TM-004, Glued Timber Products, to supersede AS/NZS 1491:1996, *Finger jointed structural timber*. After consultation with stakeholders in both countries, Standards Australia and Standards New Zealand decided to develop this Standard as an Australian Standard rather than an Australian/New Zealand Standard.

This Standard incorporates Amendment No. 1 (December 2010). The changes required by the Amendment are indicated in the text by a marginal bar and amendment number against the clause, note, table, figure or part thereof affected.

The objective of this revision is to update this Standard for finger-jointing solid timber for structural products. Major changes to the previous edition include the following:

(a) The title of the Standard in this revision has been amended in order to align with the corresponding ISO Standard and to make it clear that it deals only with the finger joint. Further clarification is given in the Scope.

(b) Clarify the requirements for quality control testing.

This Standard is a performance-based document that applies to finger jointed hardwood and softwood, used directly with either structural timber or laminations of glued laminated timber.

- The general requirement for the finger joint strength is the compliance with an in-factory test which is described in clause 8.2.3, see below. Apart from that, an initial test or the like are not described in this standard.

6.4 Finger joint strength

Finger joints in batches of finger-jointed timber or structural glulam shall be deemed to meet the strength requirements of this Standard provided the provisions of Clause 8.2.3 are met.

8.2.3 *Compliance—Finger-jointed timber*

A production batch shall be deemed to comply with the requirements of this Standard when either Items (a) or (b) below are satisfied:

(a) The bending strength ($f_{b,fj}$) or tension strength ($f_{t,fj}$) of each finger joint tested for a sample taken from a production batch satisfies—

(i) $f_{b,fj} \geq 0.74\, f'_{b,timber}$; or

(ii) $f_{t,fj} \geq 0.85\, f'_{t,timber}$.

(b) The mean bending strength ($f_{b,fj,15}$) or the mean tension strength ($f_{t,fj,15}$) of the last 15 finger joints tested from the same production line satisfies—

(i) $f_{b,fj,15} \geq k_{15}\, f'_{b,timber}$; or

(ii) $f_{t,fj,15} \geq k_{15}\, f'_{t,timber}$.

Values of k_{15} are listed in Table 1.

TABLE 1

VALUES OF k_{15}

V*	0.10	0.15	0.20	0.25	0.30	0.35	0.40
k_{15}	0.91	1.00	1.12	1.25	1.39	1.55	1.73

* V is the coefficient of variation established during initial determination of joint strength by testing at least 15 specimens or from historical data recorded in quality control documents.

NOTE: Intermediate values of k_{15} can be estimated by linear interpolation from the following equation:

$$k_{15} = 0.735\, e^{2.09V}$$

- Regarding adhesive for Service class 2, a wet test with vacuum and overpressure has to be conducted, therefore an autoclave will be needed to make this test.

8.3 Assessment of adhesive bond durability for Service Class 2 or 3 exposure

8.3.1 *Sampling*

A sample of at least four joints per month shall be taken from the production for testing; specimens shall be drawn at a rate of one specimen per week.

8.3.2 *Wet conditioning of specimens*

Specimens shall be conditioned as follows:

(a) Place the finger joints in an autoclave, immerse them in water between 10°C and 27°C and weigh them down.

(b) Draw a vacuum of at least 65 kPa or at least 500 mm Hg and hold it for 1.5 h, then release the vacuum and apply a pressure of 500 ±30 kPa for 1.5 h. Repeat this vacuum-pressure cycle once more.

NOTE: For higher density species, longer pressure and vacuum cycles may be required to achieve acceptable penetration.

8.3.3 *Testing*

The specimens shall be tested in bending according to Appendix B or tension according to Appendix C and the fracture surfaces shall be examined for wood failure.

8.3.4 *Compliance*

The bond shall be deemed to meet the requirements of this Standard provided the wood failure percentages given in Table 2 are met.

TABLE 2

WOOD FAILURE

percent

	Average	Minimum
Hardwood	40	20
Softwood	60	30

NOTE: The values are to be interpreted as the average for all fingers.

- The application of PUR for finger joints seems to be ok, as it is mentioned in the standard (except for Service Class 3)

AS 5068—2006 12

APPENDIX A

ADHESIVES

(Informative)

TABLE A1

TYPE OF ADHESIVE FOR GIVEN SERVICE CONDITIONS

Description	Service Class(1)		
	1	2	3
	Interior dry	Interior—Humid, exterior protected	Interior—Hot and humid, exterior exposed
Timber EMC	≤12%	≤18%	>18% untreated timber >20% multi-salts treated softwood
Adhesive(2)	Type I or Type II	Type I or Type II, provided the temperature remains below 50°C	Type I
Adhesive examples(3)	— Aqueous polymeric isocyanates/Emulsion polymeric isocyanates — Melamine-urea formaldehyde — Phenol-resorcinol formaldehyde — Polyurethanes — Resorcinol formaldehyde — Tannin formaldehyde	— Aqueous polymeric isocyanates/Emulsion polymeric isocyanates — Melamine-urea formaldehyde — Phenol-resorcinol formaldehyde — Polyurethanes — Resorcinol formaldehyde — Tannin formaldehyde	— Phenol-resorcinol formaldehyde — Resorcinol formaldehyde — Tannin formaldehyde Important: PU(R) mentioned here --> PU(R) for finger jointing therefore ok (except for Service Class 3).

3.6.3 Conclusion

- Bending OR tension tests are needed. As described in the conclusion for AS 1328.1, it is recommended to only conduct bending tests in a first project phase as UTAS has all the necessary equipment for that. In the second phase, it makes probably sense to test also on tension to gain more knowledge about the finger joints. If this will not be possible at UTAS, tension tests are possible in Biel
- A wet test is required. → Recommendation equipment: Procurement of an autoclave or another device that allows conducting these tests (partial vacuum and overpressure) if wanted. Has to be discussed if it makes sense to test it.
- PUR seems ok for the finger joints as it is mentioned as an example for possible glues for Service Class 1 and 2

3.7 AS/NZS 4364: 2010: Timber—Bond performance of structural adhesives

3.7.1 Conditions

Skimmed over it as this standard is chiefly for adhesive producers and goes very much into the details.

3.7.2 Relevant findings

- This standard is chiefly for glue producer (see AS/NZS 4364:2010, page 5).

5 **AS/NZS 4364:2010**

STANDARDS AUSTRALIA/STANDARDS NEW ZEALAND

Australian/New Zealand Standard

Timber—Bond performance of structural adhesives

1 SCOPE

This Australian/New Zealand Standard specifies performance requirements for adhesives according to their suitability for use in prefabricated timber components for structural use in defined environmental conditions and for such adhesives for the manufacture of structural finger-jointed timber and glulam.

NOTE: This Australian/New Zealand Standard does not cover the performance requirements for adhesive bonds between structural timber components in plywood, LVL, and wood-based panel products; however, the adhesive bond requirements may be applicable to these products.

2 APPLICATION

This Australian/New Zealand Standard is intended to be used primarily by adhesive manufacturers.

-
-

- The following requirements and tests are mentioned:

CONTENTS

Page

- In terms of the for us relevant shear, delamination and creep test, there is always a test method A described in this standard (based on a Canadian standard) and as an alternative Method B, which is identical with the referred European standards EN 302-1 (shear), EN 302-2 (delamination test, described below) and 15416-2 (creep resistance). The following example shows illustratively that these requirements can be fulfilled with the respective European tests: these requirements can be fulfilled with the respective European tests:

9 AS/NZS 4364:2010

6.6.3 *Method B—Tensile shear*

When tested in accordance with EN 302-1, the tensile shear test result shall meet the requirements specified in EN 301.

6.7 **Delamination resistance**

6.7.1 *General*

Delamination tests shall be carried out in accordance with Method A, as specified in Clause 7.6.1, or Method B, as specified in Clause 7.6.2, and shall meet the requirements specified in Clause 6.7.2 or 6.7.3, as appropriate.

6.7.2 *Method A*

6.7.2.1 *Evaluation for hardwoods*

When tested in accordance with Clause 7.6, the total delamination within any one bondline shall not exceed 1.6% of the total length of the bondline in the assembly.

6.7.2.2 *Evaluation for softwoods*

When tested in accordance with Clause 7.6, the total delamination within any one bondline shall not exceed 1% of the total length of the bondline in the assembly.

6.7.3 *Method B*

When tested in accordance with EN 302-1, the delamination result shall meet the requirements specified in EN 301.

prob. mistake, should be 302-2, see 7.6.2

- It is important to mention, that for these three tests, the specimens have to be produced specifically for the test. This in contrast to the test specimens for shearing and delamination in AS 1328.1, which are cut from glulam. A creeping test, by the way, is not described in AS 1328.1, in contrast to EN 14080 (Annex B.2).
- The wood species to be tested if the glulam shall be produced of hardwood is maple. Note: Probably it would make more sense to test it with plantation E. Nitens in our project, but this has to be discussed.

AS/NZS 4364:2010 10

7 **SAMPLE PREPARATION AND TEST METHODS**

7.1 **Anti-fungal properties**

Testing for anti-fungal properties shall be in accordance with ASTM D4300.

7.2 **pH of cured adhesive film**

Testing for pH of cured adhesive film shall be in accordance with ASTM D1583.

7.3 **Wood species and density**

7.3.1 *Hardwood*

When adhesives for hardwoods are tested in accordance with Clauses 7.5 to 7.7, the tests shall be performed on hard maple (*acer saccharum* or *acer nigrum*) of density specified in Clause 7.3.3, or the species specified in the relevant EN Standard.

3.7.3 Conclusion

- Shear strength, delamination resistance and creeping resistance: Can be tested with European standards as they are identical (the Canadian standard based tests do not have to be considered): In project phase 1 it is not necessary to make these tests, as long as the shear and delamination tests in AS 1328.1 (or the ones in EN 14080) are conducted. In the second project phase, it has to be discussed if these three tests should be made; whereby the glue producer should be involved: Ideal would be if we can send him some plantation E. Nitens and he would make these tests.

- In view of EN 14080 (and therefore EN 301 and EN 15425): In this standard here and in AS 1328.1 (the “Australian way”), fewer tests are required than with the “European way”.

3.8 EN 14080: 2013: Timber structures - Glued laminated timber and glued solid timber - Requirements

3.8.1 Conditions

- Read the whole standard in detail bzw. dort wo nicht das erwähnt damit dann ich es dann sobald Bedarf genau lesen kann
- The official standard was only available in German. In English, only the final draft was available. However, only editiorial changes were made there, so to base on this draft is ok and therefore the screenshots are taken from this final draft.

3.8.2 Relevant findings

3.8.2.1 General topics

- This is THE European standard for glulam
- Covers many softwood species and poplar but no other hardwoods (standard for hardwood glulam in progress, see WI 124xxx:2018 below), although under certain circumstances other hardwoods could be used (see screenshot)

8

FprEN 14080:2013 (E)

1 Scope

This European Standard sets the performance requirements of the following glued laminated products:

— Glued laminated timber (glulam);

— Glued solid timber;

— Glulam with large finger joints;

— Block glued glulam

for use in buildings and bridges.

It also lays down minimum production requirements, provisions for evaluation and attestation of conformity and marking of glued laminated products.

This European Standard is applicable for glued laminated timber made of coniferous species listed in this standard or poplar consisting of two or more laminations having a thickness from 6 mm up to 45 mm (inclusive).

It may be possible to produce glulam made from specific hardwood species based on some provisions of this European standard. In this case Annex ZA does not apply.

-
- It has to be distinguished between the two testing types
  a) Initial type testing (list with all tests in section 6.2, table 15)
  b) Factory production control (FPC), in other standards also called Daily quality control test =Routine test (list with all tests in section 6.3, table 16)

Initial tests – MOR, MOE and further tests

- Extract table 15:

FprEN 14080:2013 (E)

Table 15 *(continued)*

Characteristics	Requirement clause	Test-/Assessment method	Test sample	Acceptance criteria
Mechanical resistance of glued laminated timber expressed as modulus of elasticity, bending strength, compressive strength, tensile strength and shear strength				
Bending strength, compressive strength, tensile strength, shear strength, modulus of elasticity, density of glued laminated timber	5.1.6.3	or 5.1.6.3 (test)	Only for glulam for which mechanical resistance is derived from full scale tests: 30 glulam specimens	5.1.6.3
Additionally for resawn glulam	5.1.7	5.1.7 (check)	-	5.1.7
Geometrical data	5.11	5.11 (check)	General	5.11

- For the Initial test, MOR and MOE can be verified from full-scale tests with glued laminated timber (it makes sense to test full-scale glulam in the project to gain knowledge and to see the how it behaves. That is better than only from classifications according to 5.14 and 5.15). The test has to be done in accordance with EN 408.
- The standard depth of the glulam is 600mm, in contrast to AS 1328.1 where it's only 300mm

5.1.3 Related material properties

The characteristic strength, stiffness and density properties of glued laminated timber shall be verified either:

— from classifications from layups and lamination properties according to 5.1.4, or

— from cross sectional layups and documented properties of boards and finger joints according to 5.1.5 or

— from full scale tests according to 5.1.6.

The characteristic strength, stiffness and density properties may be declared by reference to a strength class according to Table 3 or 4 or to a manufacturer's specific strength class. If a manufacturer's specific class name starting with GLxx is chosen (where "xx" is the characteristic bending strength) it shall be accompanied by the Company name, e.g GL 30 Any Company. For glulam having an asymmetrical layup, "ca" has to be added to the class name, e.g. GL28 ca. The class name of resawn glulam shall be marked by "s", e.g. GL24 cs. For brick bonded glulam according to I.5.2, the denomination of strength class shall be accompanied by "brick-bonded".

The characteristic bending strength shall be valid for glulam with a depth h of 600 mm and a lamination thickness of t = 40 mm. If the lamination thickness is less than 40 mm, the bending strength may be multiplied by k as given in Formula (1). For lamination thicknesses 40 mm < $t \leq$ 45 mm it is not necessary to take any strength modification into account.

$$k = \min \begin{cases} \left(\frac{40}{t}\right)^{0,1} \\ 1{,}05 \end{cases} \quad (1)$$

where

t is the lamination thickness in mm.

The characteristic tensile strength parallel to the grain shall be valid for glulam with depth h of 600 mm or width b of 600 mm.

The characteristic tensile strength perpendicular to the grain shall be valid for glulam with a stressed volume of 0,01 m^3.

The 5%-fractile of a shear modulus or a modulus of elasticity shall be estimated from the mean value by applying the ratio of $G_{g,k}/G_{g,mean}$ = 5/6 and $E_{0,g,k}/E_{0,g,mean}$ = 5/6, respectively.

For glued laminated timber members made of at least ten laminations the product ($E_{0,g,k}$ $G_{g,k}$) may be increased by a factor k = 1,40.

- For homogeneous glulam (see 5.1.6.3.2), only MOR and MOE have to be verified in full scale tests, whereas for combined glulam (see 5.1.6.3.1) further tests are necessary such as the characteristic compression strength. These tests apart from MOR and MEO are not discussed in this document as it is not in the focus of this review.

The density of a combined glulam shall be taken as the weighted densities of the lamination zones estimated as the densities of homogeneous glulam according to Table 6.

5.1.6 Verifications from full scale tests with glued laminated timber

5.1.6.1 Properties of the boards

The characteristic values of the tensile strength parallel to the grain $f_{t,0,l,dc,k}$ or the bending strength $f_{m,l,dc,k}$, the mean modulus of elasticity parallel to the grain $E_{t,0,l,dc,mean}$ and the characteristic density $\rho_{l,dc,k}$ of the boards shall be estimated and declared by tests according to Annex E.

5.1.6.2 Strength of finger joints

The characteristic flatwise bending strength of the finger joints $f_{m,j,dc,k}$ shall be estimated and declared by tests according to Annex E.

The declared characteristic flatwise bending strength of the finger joints $f_{m,j,dc,k}$ shall be not less than 1,4 $f_{t,0,l,dc,k}$.

5.1.6.3 Strength, stiffness and density properties of glued laminated timber derived from testing

5.1.6.3.1 Combined glued laminated timber

Combined glued laminated timber shall be assigned to one of the strength classes given in Table 4 or to any other manufacturer specific strength class if the characteristic bending strength parallel to the grain $f_{m,g,k}$, the mean modulus of elasticity parallel to the grain $E_{0,g,mean}$ and the characteristic density derived from full scale tests according to Annex F and the characteristic tensile strength $f_{t,0,g,k}$ and the compression strength $f_{c,0,g,k}$ parallel to the grain tested according to EN 408 and derived according to EN 14358 are not less than the declared values. Characteristic tensile strength $f_{t,0,g,k}$ and compression strength $f_{c,0,g,k}$ parallel to the grain may be taken as the values for the lamination zone having the lowest characteristic tensile strength parallel to the grain $f_{t,0,l,k}$.

The other strength and stiffness properties of a manufacturer specific strength class shall be calculated using the expressions given in Table 6.

5.1.6.3.2 Homogeneous glued laminated timber

Homogenous glued laminated timber shall be assigned to one of the strength classes given in Table 5 or to any other manufacturer specific strength class if the characteristic bending strength parallel to the grain $f_{m,g,k}$, the mean modulus of elasticity parallel to the grain $E_{0,g,mean}$ and the characteristic density $\rho_{g,k}$ derived from full scale tests according to Annex F are not less than the declared values.

The other strength and stiffness properties of a manufacturer specific strength class shall be calculated using the formulae given in Table 6.

3.8.2.2 Initial tests – Gluing

- Relevant passages regarding glue from table 15 (marked text passages will be discussed below):

Bonding strength expressed as				
Strength of finger joints in laminations for glued laminated timber	5.1.4.2 or 5.1.5.2 or 5.1.6.2	As for mechanical resistance of glued laminated timber		
Strength of finger joints in laminations for glued solid timber	5.5.4.2 or 5.2.5.2.	As for mechanical resistance of glued solid timber		
Glue line integrity of laminations in glued laminated timber or glued solid timber	5.5.5.2.2	According to Annex C (test)	for each combination of species and adhesive 10 full cross sectional specimens	5.5.5.2.2
Bending strength of large finger joints	5.3	As for mechanical resistance of glulam with large finger joints		
Bonding strength of glue lines of block glued glulam	5.5.7.2	Annex C (test) or Annex D (test)	2 specimens	5.5.5.2.2 5.5.5.2.3
Durability of bonding strength as				
Species	5.5.2	5.5.2 (check)	-	5.5.2
Moisture of timber to be bonded[b]	G.1	G.1 (test)	100 timber pieces for each species	G.1

44

FprEN 14080:2013 (E)

Table 15 *(continued)*

Characteristics	Requirement clause	Test-/Assessment method	Test sample	Acceptance criteria
Durability of bonding strength as				
Adhesive characteristics	5.5.3.1 and 5.5.3.2.1 General requirements for phenolic and aminoplastic adhesives[b]	prEN 302-1, -2, -3, -4 and -6 (test)	acc. to prEN 302-1, -2, -3, -4 and -6	The requirements for the respective adhesive type class and subclass given in prEN 301 shall be fulfilled and the conventional pressing time according to prEN 302-6 shall be declared.
	5.5.3.2.2 Additional requirements for phenolic and aminoplastic adhesives for separate application of resin and hardener for the production of finger joints in laminations	prEN 302-1, -2, -3 and B.3[b]	5.5.3.2.2	5.5.3.2.2
		and B.3	5.5.3.2.2	5.5.3.2.2
		and Annex E	5.5.3.2.2	5.1 or 5.2
	5.5.3.2.3 Additional requirements for gap filling adhesives[b]	prEN 302-6	prEN 302-6	prEN 302-6
	5.5.3.1 and 5.5.3.3 Moisture curing one-component polyurethane adhesives[b]	EN 15425 (test)	EN 15425	EN 15425
		and B.2 (test)	80	B.2
		and prEN 302-2:2011, 5.1, 2nd para. (test) or	prEN 302-2:2011, 5.1, 2nd para.	prEN 302-2:2011, 5.1, 2nd para.
		For adhesives only to be used for finger joints in larch laminations: B.3	Analogue to 5.5.3.2.2, 1st dash	B.3
		and EN 15416-5 (test)	EN 15416-5	The conventional pressing time acc. to EN 15416-5 shall be declared
	5.5.3.1 and 5.5.3.4 Emulsion polymer isocyanate adhesives[b]	EN 15425 (test)	EN 15425	5.5.3.4
		and B.2 (test)	80	B.2
		and prEN 302-6 (test)	prEN 302-6	The conventional pressing time according to prEN 302-6 shall be declared

- Finger joints (first of the two screenshots above): 5.1.4.2, 5.1.5.2 or 5.1.6. are to be tesed under standard climate on bending strength or in some cases on tension strength instead of bending strength; both according to Annex E (which refers to the test methods in EN 408). The sample number is also given in the table.

- Note: According to EN 408, the specimen's length for tension tests has to be 9 times the with or thickness respectively.
- These samples can be cut from the produced finger jointed laminations and do not have to be produced specifically for this test.

Finger joints in laminations	5.1.4.2 or 5.1.5.2	Annex E (test)	General, for each combination of species, adhesive and declared strength value: – For laminations complying with Table 1: 15 finger joints in laminations – For laminations not complying with Table 1: 100 finger joints in laminations from at least three batches	5.1.4.2 or 5.1.5.2
	5.1.6.2		For glulam for which mechanical resistance has been derived from full scale tests, for each combination of species, adhesive and cross-sectional layup: – For laminations complying with Table 1 : 30 finger joints in laminations – For laminations not complying with Table 1: 100 finger joints in laminations from at least three batches	5.1.6.2

42

FprEN 14080:2013 (E)

- Glue line integrity: To be tested in accordance with Annex C of this standard, which describes three different delamination test methods A, B and C. They are all similar (apply a partial vacuum and after overpressure and drying of the wood in varied conditions) and are very similar to the 3 delamination methods in AS 1328.1 Appendix C. They differ regarding time, pressure, drying conditions, number of cycles. The sample size is always the same (see figure C1) and the samples are cut out of the glulam produced (so no separate sample making and gluing is needed specifically for the test). However, if the cross section is big, smaller samples can be used, see marked passage in the screenshot. This is practical, because the test equipment then can be smaller.

C.3 Sampling and preparation of test pieces

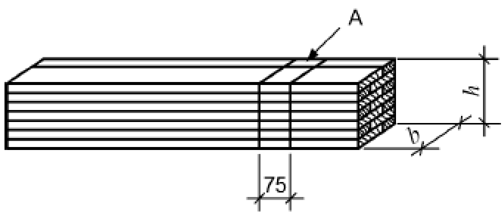
The test pieces shall be prepared or selected in such a manner that they are representative of the production run.

Each test piece shall be taken from a full cross section of the specimens to be tested, prepared by cutting perpendicular to the grain of the wood. It shall be (75 ± 5) mm in length (along the grain).

The end grain surfaces of the test piece shall be cut with a sharp saw or tool that produces a smooth surface.

If the width b of the cross section is greater than 300 mm the test piece may be lenghtwise cut into two or more test pieces each at least 130 mm wide. If the depth h is greater than 600 mm the test piece(s) may be cut into two or more pieces each with a depth of at least 300 mm (see Figure C.1).

Dimensions in mm



Key

A test piece

b width

h depth

Figure C.1 — Test piece cut from glued laminated timber having a width *b* of more than 300 mm

- The max. delamination values are defined in table 9 of this standard:

5.5.5.2.2 Glue line integrity

Where the glue line integrity is tested by the delamination test method A, B or C, given in Annex C, the total delamination percentage of each cross sectional specimen shall meet the requirements given in Table 9.

Table 9 — Maximum values for the total delamination in %

Type [a]	Number of cycles	1	2	3
Glued laminated timber, Glulam with large finger joints and block glued glulam	Method A	–	5	10
	Method B	4	8	–
	Method C	10	–	–
Glued solid timber with lamination thicknesses from 60 mm up to 85 mm (inclusive)	Method A	–	10	15
	Method B	8	12	–
	Method C	15	–	–

[a] For Glued solid timber having lamination thicknesses from 45 mm up to 60 mm linear interpolation applies.

For all delamination methods the maximum delamination percentage of a single glue line shall be less than or equal 30 %.

- Durability of bonding strength - Adhesive characteristics (table 15): Principally three different adhesive types can be used (see also a), b) and c) in the following screenshot) and they have different requirements. Noteworthy: PUR can't be used according to this standard for large finger joints and for glue lines between glulam components of block glued glulam (see table 7 following screenshot). Also important is to mention, that if preservative treatments are done before the bonding, it shall be documented that the requirements are fulfilled for the combination of the preservative and adhesive.

5.5.3 Adhesives for the production of glued laminated products

5.5.3.1 General

Adhesives shall provide durable bonds in glued laminated products throughout the lifetime of the structure for the required service class according to EN 1995-1-1. For glued laminated products used in service class 1 adhesives, which can be assigned to an adhesive type I or II according to prEN 301:2011, Table 1, or EN 15425:2008, Table 1, shall be used. For glued laminated products used in service class 2 or 3 adhesives, which can be assigned to an adhesive type I according to prEN 301:2011, Table 1, or EN 15425:2008, Table 1, shall be used.

The applicability of adhesives in different service classes may be further limited by national provisions valid at the place of use.

Emulsion polymer isocyanate adhesives shall also be assigned to an adhesive type according to EN 15425:2008, Table 1.

Taking into account the restrictions given in the referred subclauses, the following adhesive families are applicable:

a) phenolic and aminoplastic adhesives (e.g. MF, MUF, PRF, UF) in accordance with 5.5.3.2;

b) moisture curing one-component polyurethane adhesives (PUR) in accordance with 5.5.3.3;

c) emulsion polymer isocyanate adhesives (EPI) in accordance with 5.5.3.4.

If a preservative treatment is done before the bonding of the laminations it shall be documented that the requirements are fulfilled for the combination of the preservative and adhesive.

The applicability of an adhesive for a glued laminated product or its components covered by this European Standard shall be taken from Table 7.

Table 7 — Applicability of adhesives for components and products

	Relevant requirements for the application of		
	Phenolic and aminoplastic adhesives	**Moisture curing one-component polyurethane adhesives**	**Emulsion polymer isocyanate adhesives**
Finger joints in laminations for glulam and glued solid timber	5.5.3.2.1 and 5.5.3.2.2 (if relevant)	5.5.3.3	5.5.3.4
Glue lines between laminations for glulam and glued solid timber	5.5.3.2.1	5.5.3.3	5.5.3.4
Large finger joints	5.5.3.2.1 mixed before used	Not applicable	Not applicable
Glue lines between glulam components of block glued glulam	5.5.3.2.3	Not applicable	Not applicable

- Phenolic and aminoplastic adhesives shall fulfill the requirements in EN 301 and be tested according to *prEN 302-6, Adhesives for load-bearing timber structures — Test methods — Part 6: Determination of the minimum pressing time under referenced conditions* (see first of the following screenshots). EN 301 is equivalent to EN 15425, just instead of for PUR it is for phenolic and aminoplastic adhesives and refers to many test standards such as EN 302-1, 302-2 etc. (see second of the following screenshots, note that it is from an outdated version but gives anyway an idea about the many tests required). As at the moment in our project probably PUR will mainly be predominately used, EN 301 is not discussed further. However, this has to be done if the use of phenolic and aminoplastic adhesives will be envisaged.

31

FprEN 14080:2013 (E)

5.5.3.2 Phenolic and aminoplastic adhesives

5.5.3.2.1 General requirements

Phenolic and aminoplastic adhesives shall fulfil the requirements of prEN 301 and shall be tested according to prEN 302-6.

New:

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

EN 302-1, *Adhesives for load-bearing timber structures - Test methods - Part 1: Determination of longitudinal tensile shear strength*

EN 302-2, *Adhesives for load-bearing timber structures - Test methods - Part 2: Determination of resistance to delamination*

EN 302-3, *Adhesives for load-bearing timber structures - Test methods - Part 3: Determination of the effect of acid damage to wood fibres by temperature and humidity cycling on the transverse tensile strength*

EN 302-4, *Adhesives for load-bearing timber structures - Test methods - Part 4: Determination of the effects of wood shrinkage on the shear strength*

EN 408, *Timber structures - Structural timber and glued laminated timber - Determination of some physical and mechanical properties*

EN 923, *Adhesives - Terms and definitions*

EN 1245, *Adhesives - Determination of pH*

EN 1995-1-1, *Eurocode 5: Design of timber structures - Part 1-1: General - Common rules and rules for buildings*

EN 12092, *Adhesives - Determination of viscosity*

EN 13183-2, *Moisture content of a piece of sawn timber - Part 2: Estimation by electrical resistance method*

5

DIN EN 301:2013-12
EN 301:2013 (E)

- Regarding PUR adhesives, in this standard, it is referred to Annex B.2 and EN 15425. EN 15425 refers to many other very detailed tests (one of which is EN 302-2 which is explained below). EN 15425 is described below in 3.11, including a screenshot with the many tests referred to. In Annex B.2, a long-term test is conducted over up to 12 months at cyclic climate conditions. EN 15416-5 (Adhesives for load-bearing timber structures other than phenolic and aminoplastic — Test methods — Part 5: Determination of conventional pressing time) should be considered for PUR as long as the glue producer cannot clearly recommend a minimal pressing time for the glue used at envisaged pressing pressure, the given temperature and wood moisture content of the plantation E. Nitens. Alternatively, at least in the first project phase, an own-developed simpler test could be made to get an indication about the minimal pressing time.

5.5.3.2.3 Additional requirements for gap filling adhesives

The minimum conventional pressing time of a glue line having a thickness of 1 mm shall be determined as specified in prEN 302-6.

5.5.3.3 Moisture curing one-component polyurethane adhesives

Moisture curing one-component polyurethane adhesives shall fulfil the requirements of EN 15425 and B.2 taking into account the conditions given in B.1.

The requirements given in prEN 302-5:2011, 5.1, 2nd paragraph apply. For moisture curing one-component polyurethane adhesives to be used in finger joints in larch wood the delamination test according to prEN 302-2 may be replaced by tests according to Annex B.3 with larch wood.

The influence of the climate on the conventional pressing time shall be verified in accordance with EN 15416-5.

5.5.3.4 Emulsion polymer isocyanate adhesives

5.5.3.4.1 General

Emulsion polymer isocyanate adhesives shall only be used for glued laminated products to be used in service classes 1 and 2.

Emulsion polymer isocyanate adhesives shall be tested in accordance with EN 15425 and B.2 taking into account the conditions given in B.1 and the respective requirements shall be fulfilled.

32

FprEN 14080:2013 (E)

- Note: For the initial tests, mostly the samples have to be made specifically for the test and can't just be cut from the glulam (in contrast to the tests for the Factory production control see below). As an example, see the description of EN 302-2.

3.8.2.3 Factory production control (FPC) – MOR, MOE and further tests

- There are no tests that go further than the initial tests according to the following screenshot, where also the test frequency is given. All these tests can be done with samples from the glulam production process and don't have to be made specifically for the tests.

FprEN 14080:2013 (E)

Table 16 — Factory production control for glued laminated products

Property	Clause, indicating the relevant test or evaluation method	Acceptance criteria	Minimum frequency
Mechanical resistance of glued laminated products			
Strength, stiffness and density properties of timber	5.1.2	General, for timber graded by the manufacturer of the glued laminated products: EN 14081-1:2011, 6.3	According to EN 14081-1:2011, 6.3
		General, for timber not graded by the manufacturer of the glued laminated products: -	Check suppliers declaration according to EN 14081-1:2011, Clause 7, on receipt
	E.5	Additionally for glulam for which mechanical resistance has been derived from full-scale tests: $f_{m,k,l}$ determined according to E.5 shall be greater than or equal to $f_{m,k,l,dc}$ (determined within ITT)	2 boards per shift and line, layup, strength class or manufacturer specific strength class
Finger joints in laminations	Annex E	see E.3 and declared values according to 5.1.4.2 or 5.1.5.2 or 5.1.6.2 (glulam) or 5.2.4.2 or 5.2.5.2 (glued solid timber)	at least 3 per shift and line, highest strength class or manufacturer specific strength class and adhesive

-

3.8.2.4 Factory production control (FPC) – Gluing

- Compared to the initial tests, there are no other tests or tests that go further than those. Only exception: The shear test (Annex D, the test is described below) which can be done instead of the delamination test (Annex C). To replace the delamination test by the shear test should not be realised as both tests provide important information about the glue line (for this reason it is common practice to test both – delamination and shear). The test frequency is also given here.
- All these tests can be done with samples from the glulam production process and do not have to be made specifically for the tests.

Bonding strength			
Finger joints in laminations	5.1.4.2 or 5.1.5.2 or 5.1.6.2 (glulam) or 5.2.4.2 or 5.2.5.2 (glued solid timber)	As for mechanical resistance	
Bonding strength of glue lines in glued laminated timber or glued solid timber	Annex C	see 5.5.5.2.2	for each shift in which gluing is carried out one full cross sectional specimen for each 20 m^3 of production or part thereof.[a]
	or Annex D	see 5.5.5.2.3	
	I.5.8	I.5.8	
Large finger joints	I.6.6	I.6.6	at each change of dimension, at least one per shift
Bonding strength of block glued glulam	method B as given in Annex C	see 5.5.5.2.2	for each shift in which gluing is carried out, each species and adhesive at least two drill cores having a geometry as given in Figure D.7 or one end-cut[b]
	or Annex D	see 5.5.5.2.3	
	I.7.4	I.7.4	

50

Table 16 *(continued)*

Property	**Clause, indicating the relevant test or evaluation method**	**Acceptance criteria**	**Minimum frequency**
Durability of bonding strength			
Species	5.5.2	5.5.2	Check the suppliers declaration at each reception
Adhesive	5.5.3	-	Adhesives for the production of finger joints or glue lines between laminations: Check the suppliers declaration at each reception Adhesives for large finger joints or glue lines between components of block glued glulam: At each shift in which products are produced
Moisture content of timber to be jointed	G.1	G.1	Measurement according to the quality manual of the manufacturer of the glued laminated product
	and G.2 (if relevant)	G.2	At least one measurement per month
Durability of other characteristics against biological attack			

- Test method of the shear test in Annex D in brief: Small specimens cut from the glulam produced (no separate making and gluing of samples), testing of the glue line parallel to the grain in dry conditions (20°C, 65% relative humidity). Test very similar to or even the same as the one in AS 1328.1 and the minimum wood failure percentages are given in table 10 (note: it's the same table as in AS 1328.1):

5.5.5.2.3 Shear strength of glue lines

Where the shear strength of the glue lines is tested according to Annex D, each test result shall comply with the following requirements with regard to the shear strength and the wood failure percentage.

The shear strength of each glue line shall be at least 6 N/mm², see Table 10, individual values. A shear strength of 4 N/mm^2 shall be regarded as acceptable if the wood failure percentage is 100, see Table 10, individual values.

The average wood failure percentage of a cross sectional specimen and any individual values shall exceed the minimum wood failure percentages stated in Table 10.

34

FprEN 14080:2013 (E)

Table 10 — Minimum wood failure percentages relating to the shear strength f_v[a]

	Average			Individual values		
Shear strength f_v, in N/mm^2	**6**	**8**	**$f_v \geq 11$**	**$4 \leq f_v < 6$**	**6**	**$f_v \geq 10$**
Minimum wood failure percentage, in %[b]	90	72	45	100	74	20

[a] For values in between linear interpolation shall be used.

[b] For average values the minimum wood failure percentage shall be: $144 - (9 f_v)$. For the individual values the minimum wood failure percentage for the shear strength $f_v \geq 6{,}0$ N/mm^2 shall be: $153{,}3 - (13{,}3 f_v)$.

-
-

____

3.8.3 Conclusion

- The standard does not cover hardwood (apart from poplar)
- Compared to AS 1328.1 there are several differences and considerably more tests referred to. Here some examples:
    - Many of the tests in EN 301 (for phenolic and aminoplastic adhesives) and EN 15425 (for PUR adhesives are not mentioned or described in AS 1328.1
    - PUR is well covered in EN 14080, whereas it's not mentioned in AS 1328.1
    - For full-scale tests, the standard depth of the glulam beam is 600mm in EN 14080 and 300mm in AS 1328.1
- In a first project phase we should focus on the tests that are important and at the same time can be easily made (ideally specimens cut out of the glulam and not to be made only for the test). A possible approach could be:
    - Full-scale bending tests. If possible adapt the test machine at the Inveresk campus, so that longer and thus deeper beams can be tested. Alternatively, they can be tested in Biel.
    - Finger joints: Bending tests (in the second phase, also tension test to get more knowledge)
    - Delamination tests concerning face bonding according to Annex C (in the second phase also according to EN 302-2) Recommendation equipment: Procurement of an autoclave or an other device that allows delamination tests (partial vacuum and overpressure).
    - Shear test according to Annex D (in a later stage also according to EN 302-1). Note: This test is not needed according to the standard as long the delamination is tested. But it makes sense to do it as it gives valuable information about the mechanical strength of the bonding (for this reason it is common practice to test both – delamination and shear).
- As already said in the section of AS 4364, in the second project phase, also the other tests have to be considered if the glulam has to be fully in accordance with the standard. These tests are mostly tests where the specimens have to be made specifically for the test – samples cannot just be cut out of the glulam. It would be good if the glue producer could be involved: Ideal would be if we can send him some plantation E. Nitens and he would make these tests.
- One test to be discussed could be the one regarding minimal pressing time as this topic is mentioned many times in this standard. If the glue producer cannot give a clear recommendation for the glulam in this project, it could be tested with a simple self-developed test or according to EN 302-6 or EN 15416-5 respectively if it should be tested in line with the standards.
- Another test to be discussed is the long-term (creeping test) according to Annex B.2, if PUR (or EPI) is used. It has to be decided, whether it should be carried out or not.

3.9 WI 124xxx:2018 (IN PROGRESS): Timber structures — Hardwood glued laminated timber — Requirements

3.9.1 Conditions

- Skimmed over it as it is a draft in progress and still by far not complete.
- Looked for the terms "eucalyptus", "nitens" and "plantation" to make sure that there are no restrictions for plantation E. Nitens or eucalyptus or plantation timber in general.

3.9.2 Relevant findings

- No restrictions regarding hardwood species or plantation timber
- According to the Christophe Sigrist (2019), the final version is estimated to be published in 2021.
- In terms of glue and bonding, this standard seems to be similar to EN 14080 (with some differences though):
    - Shear strength and delamination resistance mentioned
    - However, creep resistance is not mentioned
    - Shear strength: Apart from a «wet shear test», also a «wet shear test» is envisaged (no description about it there so far), see WD W1 124xxx:2019 (E), page 20
    - Delamination test: Similar - identical to the ones in EN 14080

- Only adhesive type I is allowed and the use of PUR is generally ok:

  WD WI 124xxx:2019 (E)

  1 Scope

  This European Standard sets out requirements regarding the performance of characteristics of the following types of glued laminated products made of hardwood (hardwood glued laminated products) to be used in buildings and bridges:

  — Type 1: hardwood glued laminated timber (hardwood glulam);

  — Type 2: hardwood block glued glulam.

  NOTE Glued laminated timber made of specific softwoods and poplar is covered in EN 14080.

  It also lays down procedures for assessment and verification of constancy of performance (AVPC) of characteristics and specifies marking and labelling.

  This European Standard covers hardwood glued laminated products:

  — manufactured according to this standard, which sets up provisions for:

    — boundary conditions during manufacture;

    — moisture content and temperature of timber to be bonded;

    — combinations of species and adhesives;

    — lamination and overall sizes;

    — production of finger joints and bonds between layers;

    — production of glue lines between hardwood glulam components (for Type 2 only).

  — bonded with phenolic or aminoplastic or moisture curing one-component polyurethane or emulsion polymer isocyanate adhesives of adhesive type I according to the respective adhesive standard;
- Many of the standards referred in this standard (see WD W1 124xxx:2019 (E), page 6 and 7) are the same as the ones referred to in EN 14080

3.9.3 Conclusion WI 124xxx:2018 (IN PROGRESS):

- Nothing to consider at the moment as the standard is not complete at all so far and much will change again until its estimated publication of the final version in 2021.
- But it's important to well observe updated draft versions and final version and take action if necessary (consider new tests or adapt the ones from AS 1328.1 or EN 14080)
- Generally speaking, because this will be the first standard for glulam made of hardwood and because it refers to many other standards also referred to in EN 14080: From this standpoint of view it consequently seems reasonable to go the "European way" with EN 14080 (as then this standard WI 124 is better covered) as far as possible rather than the Australian one with AS 1328.1.

3.10 **EN 408:2010-12: Timber structures – Structural timber and glued laminated timber – Determination of some physical and mechanical properties**

3.10.1 Conditions

Skimmed over it as this standard is more about mechanical strength than about glue and glue line. However, the relevant information about the bending test is read in detail.

3.10.2 Relevant findings

- In contrast to AS 1328.1 (respectively in the therein referenced AS 4063.1), the span can be reduced from 18h to 15h thanks to the tolerance of 1.5h on each side. The distance between the two upper loading heads, however, has to be 6h as in AS 4063.1 and can't be reduced.
- The reduction of the span could help to test deeper glulam on the bending test machine in the Inveresk campus.

DIN EN 408:2012-10
EN 408:2010+A1:2012 (E)

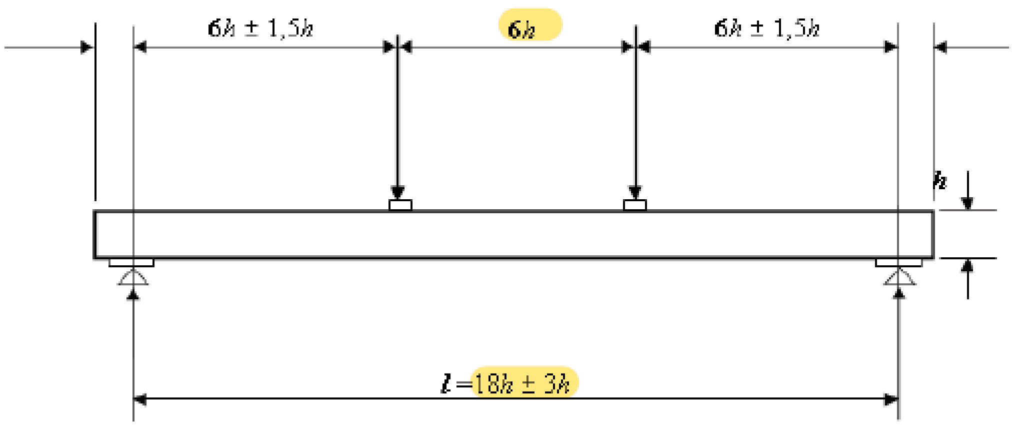


Figure 17 — Test arrangement for measuring bending strength

3.10.3 Conclusions

The possibility of the reduced span on the «European way» has to be taken into account when it is about to test beams as deep as possible.

3.11 EN 15425:2017: Adhesives - One component polyurethane (PUR) for load-bearing timber structures - Classification and performance requirements

3.11.1 Conditions

- Skimmed over it as this standard goes deep in the details and is at least partly rather relevant for the glue producer than for the glulam producer

3.11.2 Relevant findings

- This standard refers to a wide array of test methods to be fulfilled by the glue itself, and not of the bonding properties in the glulam. Hence, all or at least most of the samples have to be made specifically for this test and can't be cut from the glulam.
- Many go deep into the detail, for example *EN 302-4: Adhesives for load-bearing timber structures - Test methods - Part 4: Determination of the effects of wood shrinkage on the shear strength*. Further, for many of the tests, the glue line has to be thick, for example 0.5 or 1mm thick. An idea of the many tests referred to in this standard gives the following screenshot: new:

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

EN 302-1, *Adhesives for load-bearing timber structures - Test methods - Part 1: Determination of bond strength in longitudinal tensile shear strength*

EN 302-2, *Adhesives for load-bearing timber structures - Test methods - Part 2: Determination of resistance to delamination*

EN 302-3, *Adhesives for load-bearing timber structures - Test methods - Part 3: Determination of the effect of acid damage to wood fibres by temperature and humidity cycling on the transverse tensile strength*

EN 302-4, *Adhesives for load-bearing timber structures - Test methods - Part 4: Determination of the effects of wood shrinkage on the shear strength*

EN 923:2005, *Adhesives - Terms and definitions*

EN 1995-1-1, *Eurocode 5: Design of timber structures – Part 1-1: General - Common rules and rules for buildings*

EN 15416-2, *Adhesives for load bearing timber structures other than phenolic and aminoplastic - Test methods - Part 2: Static load test of multiple bondline specimens in compression shear*

EN 15416-3, *Adhesives for load bearing timber structures other than phenolic and aminoplastic - Test methods - Part 3: Creep deformation test at cyclic climate conditions with specimens loaded in bending shear*

EN 15416-4, *Adhesives for load bearing timber structures other than phenolic and aminoplastic - Test methods - Part 4: Determination of open assembly time for one component polyurethane adhesives*

EN 15416-5, *Adhesives for load bearing timber structures other than phenolic and aminoplastic - Test methods - Part 5: Determination of conventional pressing time*

4

DIN EN 15425:2008-06
EN 15425:2008 (E)

-
- The most relevant tests seem to be the shear test (EN 302-1Adhesives for load-bearing timber structures — Test methods — Part 1: Determination of longitudinal tensile shear strength), the test about compression time for PUR (EN 15416-5, Adhesives for load-bearing timber structures other than phenolic and aminoplastic – Test methods - Part 5: Determination of conventional pressing time) and the delamination test EN 302-2, see below.

3.11.3 Conclusion

- For the first project phase, it is for sure not necessary to consider all the tests referred to in this standard as this would go way too far. In the second phase however it has to be decided if some of these tests such as EN 302-1 and 302-2 (both initial tests) shall be tested or if the shear (Annex D) and delamination tests (Annex C) in EN 14080 (both routine tests) are enough – be it short or long-term in this project.
- Regarding pressing time, see comment in the conclusion of EN 14080

3.12 **EN 302-2: 2017: Adhesives for load-bearing timber structures - Test methods - Part 2: Determination of resistance to delamination**

3.12.1 Conditions

- Read the whole standard in detail

3.12.2 Relevant findings

- Specimens have to be produced specifically for this test, in contrast to AS 1328.1 and EN 14080, where samples are used which are cut from the glulam.
- The test is for an initial test according to EN 14080, table 15 (initial test where EN 302-2 is a requirement). It is not for the Factory production control (FPC) test (=Routine test).
- All wood species are covered and the wood species that is intended to be used for the glulam has to be tested (in case we would thus use plantation E. Nitens)
- There are two types of test: One for adhesive type II and a harsher one for adhesive Type I
- Describes also the test for a glue line of 2mm thickness. Not relevant to us.
- Test parameters for testing the samples (s. screenshot) similar like in AS 1328.1 and EN 14080, but differ for example concerning pressure, times, number of cycles.

10

DIN EN 302-2:2017-11
EN 302-2:2017 (E)

Table 2 — Cyclic treatments for the delamination test

Treatment	Parameters	Units	High temperature procedure for Type I adhesive	Low temperature procedure for Type II adhesive
Water impregnation	Water temperature	°C	10 to 25	10 to 25
	Absolute pressure	kPa	25 ± 5	25 ± 5
	Duration	min	15	15
	Absolute pressure	kPa	600 ± 25	600 ± 25
	Duration	h	1	1
	Nr impregnation cycles	-	2	2
Drying	Air temperature	°C	65 ± 3	27,5 ± 2,5
	Air humidity	%	12,5 ± 2,5	30 ± 5
	Air circulation[a]	m/s	-	-
	Duration	h	20 ± 2	90 ± 6
	Number of complete cycles (A cycle consists of two water impregnation treatments and one drying treatment.)	-	3	2

[a] Air circulation of 2 m/s to 3 m/s in empty chamber has proven to be suitable.

3.12.3 Conclusion

- The test is for an initial test and test principles similar to AS 1328.1 and EN 14080
- Specimens have to be produced specifically for this test, in contrast to AS 1328.1 and EN 14080, where samples are used which are cut from the glulam.
- Probably this test has not to be conducted in a first phase in the project as delamination is already covered with annex C of EN 14080 annex and also with AS 1328.1. However, in a second phase, to be in line also regarding the initial test, it would be better also to test the delamination in accordance to this standard EN 302-2 – Unless the glue producer can make this test.
- Recommendation equipment: If we aim to make this test: Procurement of an autoclave or other device that allows delamination tests (partial vacuum and overpressure). Note: Also if we don't will make this test, we anyway have to test delamination (eg. According to AS 1328.1 or EN 14080 Annex C) and to procure the corresponding apparatus.

3.13 List with the most important tests required according to the standards

Australian standards					
No	Required as per[1]	Test// according to//(description)	Initial test or routine	Frequency[2] + sample number	Comments
1	AS/NZS 1328.1 p. 8	Bending test MOE and MOR// AS/NZS 4063// on completed 300mm deep glulam members	Initial	One glulam member (AS/NZS 1328.1 p. 9)	characteristics could also be determined from lamination properties (method 2 AS/NZS 1328 p. 9)
2	AS/NZS 1328.1 p. 11	Delamination test (if methods A, B or C depends on various factors see table 2.1 AS/NZS 1328.1)// AS/NZS 1328.1 Appendix C// on full manufactured glulam cross sections 75mm long	Initial	min. 5 samples (AS/NZS 1328.1 p. 10)	
3	AS/NZS 1328.1 p. 11	Delamination test with method C (for service class 1 and 2)// AS/NZS 1328.1 Appendix C// on full manufactured glulam cross	Routine	1 sample for each shift for each press lead or every 10m3 of production (AS/NZS 1328.1 p. 10)	For this routine test, either the delamination test (method C Appendix C) OR the block shear test has to be made (for service class 1 and 2)
4	AS/NZS 1328.1 p. 11	Block shear test// AS/NZS 1328.1 Appendix D// from a full manufactured glulam cross section 40-50mm long	Routine	1 sample for each shift for each press lead or every 10m3 of production (AS/NZS 1328.1 p. 10). Frequency can be reduced if after 3 month all tests are satisfying,	
5	AS/NZS 1328.1 p. 9	Stress assessment on joints on bending// AS 5028 p. 7 + 10// bending strength	Routine	Method a): each finger joint from a sample taken from a production batch Method b): At least 15 finger joints tested from the same production line	AS 5028 p. 10: Tension strength could be tested instead of bending strength. Described on the same pages as the described bending tests. // AS/NZS 1328.1 p. 17: Instead of sample testing (described here), the verification can also be done
6	AS/NZS 1328.1 p. 9	Adhesive bond durability for Service Class 2 + 3 // AS 5028 p. 11 and Appendix B// bending with wet specimen	Routine	One sample of at least four joints per month from the production, at a rate of one specimen per week (AS 5028 p. 11)	AS 5028 p. 11: Instead of bending, the test could also be made on tension
7	AS/NZS 4364 p. 8 + 9 (to AS/NZS 4364 is referred in AS/NZS 1328.1 p. 2+8+15)	Shear strength and wood failure// EN 301, EN 302-1 // shear test on samples made specifically for the test	Initial (respectively it's about the glue itself)	No information about sample number, because EN 302-1 could not be procured	
8	AS/NZS 4364 p. 9 (to AS/NZS 4364 is referred in AS/NZS 1328.1 p. 2+8+15)	Delamination resistance// EN 301, EN 302-2 // delamination test on samples made specifically for the test	Initial (respectively it's about the glue itself)	Samples 75 x ca. 150 x ca. 150mm: Four with minimum and four with maximum closed assembly time (EN 302-	

European standards					
No	Required as per[1]	Test// according to//(description)	Initial test or routine	Frequency[2] + sample number	Comments
9	EN 14080 p. 18, 19, 26, 43	MOE and MOR test glulam// EN 14080 Annex F, EN 408 // full scale test (standard depth 600mm)	Initial	30 glulam specimens (EN 14080 p. 43)	Instead of full scale test, the verification could also be made by classifications from layups and lamination properties or from cross sectional layups (14080 p. 18
10	EN 14080 p. 26, 42-44	Strength of finger joints in lamination by bending // EN 14080 Annex E, EN 408 // test of the whole jointed cross section of the lamination	Initial	Depending on the circumstances (EN 14080 p. 42+43) either 15, 30 or 100 finger joints in laminations	
11	EN 14080 p. 26 + 50	Strength of finger joints in laminations by bending // EN 14080 Annex E, EN 408 // test of the whole jointed cross section of the lamination	Routine	at least 3 per shift and line, highest strength class or manufacturer specific strength class and adhesive (EN 14080	Under certain circumstances, instead of bending tests, tension tests can be made which have to be carried out according to EN 14080 Annex E
12	EN 14080 p. 34 + 44	Delamination test // EN 14080 Annex C // cross sections 75mm long cut from manufactured glulam	Initial	10 full cross sectional specimens (under certain circumstances smaller size then full cross section possible, see EN 14080 p. 64)	
13	EN 14080 p. 34 + 50	Delamination test // EN 14080 Annex C Method A, B or C // cross sections 75mm long cut from manufactured glulam	Routine	1 full cross sectional specimen for each 20m³ of production or part of thereof (reduction of number of samples possible under certain circumstances), see EN 14080 p. 50 note "a"	For factory production control either this delamination test has do be conducted OR the shear strength test below (No 14)
14	EN 14080 p. 34 + 50	Shear strength of glue lines // EN 14080 Annex D // cross sections 75mm long cut from manufactured glulam	Routine	1 full cross sectional specimen for each 20m³ of production or part of thereof (reduction of number of samples possible under certain circumstances), see EN 14080 p. 50 note "a"	For factory production control either this shear test has do be conducted OR the delamination test above (No 13)
15	EN 14080 p. 32 + 45	Shear strength// EN 301 respectively EN 15425, EN 302-1 // shear test on samples made specifically for the test	Initial	No information about sample number because EN 302-1 could not be procured	
16	EN 14080 p. 32 + 45	Delamination resistance// EN 301 respectively EN 15425, EN 302-2 // Delamination test on samples made specifically for the test	Initial	Samples 75 x ca. 150 x ca. 150mm: Four with minimum and four with maximum closed assembly time (EN 302-	
17	EN 14080 p. 32 + 45	creep test (long-term load at cyclic climate conditions)// EN 14080 Annex B.2// samples ca. 50 x 50 x 50mm made specifically for the test and test lasts up to 12 months	Initial	80 samples	This test only applies for PUR and EPI, not for phenolic and aminoplastic adhesives
18	WD W1 124xxx p. 20	wet shear test// WD W1 124xxx p. 20 Annex F// shear test in wet conditions	Routine	one full cross sectional specimen for each 20 m³ of production or part thereof	Standard still in progress; hence it could change

[1]Issue and title of the standard see in the standard overview of this report

[2]Frequency for initial tests: It's just one time at the beginning (of a new wood species, glue, production parameter etc.)

4. **Conclusion/ Recommendations**

The glulam standard for Australia is AS/NZS 1328.1 and for Europe it is EN 14080. The Australian standard doesn't have any restrictions regarding (plantation) wood species, while the European standard only covers softwoods and poplar. Nevertheless, although hardwood is not covered apart from poplar, EN 14080 gives a good idea of the manifold tests that need to be taken to ensure reliable bonding in glulam. Further, a European standard for hardwood glulam is currently being written, which will then provide hardwood specific requirements and tests.

Several points are similar or even identical in the Australian and European standards. For instance, both differ between initial tests and factory production control (also called routine tests). Some of the Australian initial tests are identical to the EU ones (e.g. requirements for shear strength and delamination resistance in AS 4364 can be tested according to EN 302-1 and EN 302-2). Further, for both standards it is possible to test finger joint strength with bending OR tension tests. Apart from the similarities, there are also considerable differences. The most important ones are:

- EN 14080 refers to many more tests (especially via EN 301 (relevant for phenolic or aminoplastic adhesives) and EN 15425 (relevant for PUR adhesives)) than AS 1328.1 and AS/NZS 4364. However, many of these tests go deep into the detail and concern mainly or at least to a high degree the glue producer.
- Nevertheless, this fact shows that there are several aspects to consider for glulam bonding which are not covered by 1328.1, probably because it is based on the outdated standard BS EN 385:1995. For example, PUR adhesive and requirements for it are nowhere mentioned in AS 1328.1, while in EN 14080 this important topic is well covered via EN 15425 where many detailed tests are listed.
- In AS 5068, for glulam in service class 2 and 3, a wet test for the finger joints is required (on bending OR tension), while in the European standards all finger joint-related tests are carried out in dry conditions

The only standard for glulam made of hardwood will be the new standard *WI 124xxx:2018 (IN PROGRESS): Timber structures — Hardwood glued laminated timber — Requirements*. Many things in there are similar to EN 14080 and many standards referenced to in this hardwood glulam draft are also referenced to in EN 14080. It can be expected that the final version will be published in 2021.

In terms of bending tests, the finger joint strength can be tested with a bending test according to both, the Australian and European standards. Also, in both standards, full scale bending tests are described to test the glulam. A big difference there is, however, that the standard depth of the beam is 300mm in AS 1328.1 and 600mm in EN 14080.

As seen, the glulam standards require a lot of tests. As a recommendation, it hence seems to make sense to divide the project into two phases:

- Phase 1
    - Most relevant tests
    - Small sample number
    - Tests that can be done quickly (test equipment is ready at the industrial partner, UTAS or Biel)
    - Preferably with samples cut from glulam (or the whole glulam beam respectively for full scale tests) produced by the industrial partner(s) or in the case of finger joints from laminations. The tested finger joints should be produced industrially.
    - Goal: Evaluate the potential of glulam with plantation E. Nitens, get a feeling for the material, the glue, the bonding and to identify possible traps and difficulties
- Phase 2
    - Same tests as in phase 1 but more sample numbers, if necessary optimised parameters (pressing time, adapted glue etc.)
    - Further tests (eg. where samples can't be cut from the glulam but have to be made specifically for the tests)

- Goal: Statistically and technically underly and confirm the results from phase 1, bringing the glulam closer in line with the standards thanks to more tests, fine-tuning of process parameters

This 2-step-approach allows getting quickly first results which then help to determine how to proceed further. According to this standard review (to remember: Only the topics glue, bonding and bending tests are covered), for phase one, the following tests could be made:

- Glue/ bonding:
  - Delamination test (either according to AS 1328.1 Appendix C or EN 14080 Annex C)
  - Shear test (either according to AS 1328.1 Appendix D or EN 14080 Annex D)
- Finger joints
  - Test of finger joint strength with bending test (be it according to AS 1328.1/ AS 5068 or EN 14080). The tested finger joints should be produced industrially.
  - To be discussed: If the wet test as mentioned in AS 5068 makes sense or not.
- Bending tests
  - Full scale tests at UTAS Inveresk on glulam beams produced by the industry partner(s). Possibly the beams should be deeper than 300mm and with ideally 15 laminations (the bigger, the closer it is to the European standard test beam which is 600mm deep). Consider hereby EN 408, where the span can be 15h instead of 18h.
  - Test of finger joint strength
- If the tests shall be made only with one glue system (the one most likely used by the industrial partner, eg. PUR adhesive) or in addition with a second one (eg. a phenolic or aminoplastic adhesives such as MF, MUF, PRF, UF) has to be discussed. A second one would certainly be interesting to compare to the first one and would provide a broader idea about glue systems.
- *Note: In view of CLT made of plantation E. Nitens which is probably face glued by a vacuum press, it maybe makes sense to apply for these tests the same cramping pressure as with the vacuum press (to gain knowledge for CLT face gluing). Alternatively, higher pressure can be used for the majority of the glulam/ the samples and some with the pressure according to the vacuum press → interesting comparison regarding the influence of the pressure on bonding performance and glue line thickness is possible.*

Regarding equipment, it would be good if delamination tests can be made by the industrial partner or by UTAS (procurement of an autoclave, while a dryer is already available at UTAS). For the bending test, and adaptation to test bigger beams would be good. If this costs to much, the tests can be done in Biel.

Which tests should be made in phase 2 depends significantly on the results of the tests in round one. Further, at the beginning of phase two, the conclusions and recommendations in this section should be considered anew to determine which tests should be conducted. Anyway, from today's standpoint of view the following tests could make sense (just as a rough guideline):

- The same tests as in phase one but with more samples to underly and confirm it statistically
- Glue/ bonding:
  - Delamination test according to EN 302-2 (it's an initial test, sample to be made specifically for the test)
  - Shear test according to EN 302-1 (it's an initial test, sample to be made specifically for the test)
  - Long-term sustained load test at cyclic climate conditions (EN 14080 Annex B.2)
  - In case the glue producer is not able to clearly recommend the minimal pressing time, it has to be discussed if tests shall be made for that: Be it according to the standards EN 302-6 or EN 15416-5, or just a smaller self-developed test
  - There is a wide range of further tests referred to in EN 14080 (respectively in the therein referred standards EN 301 and EN 15425). It has to be discussed at that stage whether some of these shall be tested or not[1].
- Finger joints

- Apart from the tests on bending in phase 1, also tests tension, be it according to AS 1328.1/ AS 5068 or EN 14080. Also here, as in phase 1, the finger joints should be produced industrially.

- Bending tests
  - Full scale tests on glulam beams, now in phase two they should definitively be deeper than 300mm, e.g. 450mm deep or even 600mm deep. This could be done in Biel if it is not possible at UTAS in Inveresk. Consider hereby EN 408, where span can be 15h instead of 18h.

[1]For these many and often very detailed tests, it is important to involve the glue producer if possible: If he can do some of these tests with E. Nitens and the glue envisaged, this would be ideal. Also helpful would be, if he makes these tests with other hardwood: It could be a useful indication for how the glue would perform on E. Nitens.

To sum up again regarding Australian versus European standards: As seen, EN 14080 covers more aspects of gluing than the Australian standards do and the latter ones sometimes are identical with the European ones. For this reason, it seems to be good if as many tests as possible are made in line with European standards. An advantage of that would be, that this way we would be already closer to the coming standard for hardwood glulam and for future international commercialization of the E. Nitens glulam this would also be advantageous, as European standards for timber products are globally better known and accepted than the Australian ones. In terms of the new hardwood glulam standard, it is very important, to well observe the updated drafts and to react and adapt the project/ test methodology if necessary.

5. **Reference list**

5.1 Australian standards

Australian Building Codes Board (2019) *NCC 2019 Building Code of Australia - Volume One.* Available at: https://ncc.abcb.gov.au/ncc-online/NCC (Accessed: 1 May 2019).

Australian Building Codes Board (2019) *NCC 2019 Building Code of Australia - Volume Two.* Available at: https://ncc.abcb.gov.au/ncc-online/NCC (Accessed: 1 May 2019).

Australian Building Codes Board (2019) *NCC 2019 Building Code of Australia - Volume Three.* Available at: https://ncc.abcb.gov.au/ncc-online/NCC (Accessed: 1 May 2019).

Australian Building Codes Board (2019) *NCC 2019 Guide to BCA Volume One.* Available at: https://ncc.abcb.gov.au/ncc-online/NCC (Accessed: 1 May 2019).

Standards Australia (2010) *AS 1684.2 — 2010 (Incorporating Amendment Nos 1 and 2): Residential timber-framed construction - Part 2: Non-Cyclonic Areas.* Available at: https://www-saiglobal-com.ezproxy.utas.edu.au/online/autologin.asp (Accessed: 3 April 2019).

Standards Australia (2010) *AS 1684.3 — 2010 (Incorporating Amendment No. 1): Residential timber-framed construction - Part 3: Cyclonic Areas.* Available at: https://www-saiglobal-com.ezproxy.utas.edu.au/online/autologin.asp (Accessed: 3 April 2019).

Standards Australia (2010) *AS 1684.4 — 2010 (Incorporating Amendment No. 1): Residential timber-framed construction - Part 4: Simplified—Non-Cyclonic Areas.* Available at: https://www-saiglobal-com.ezproxy.utas.edu.au/online/autologin.asp (Accessed: 3 April 2019).

Standards Australia (2010) *AS 1720.1–2010 (Incorporating Amendment Nos 1, 2 and 3): Timber structures - Part 1: Design methods.* Available at: https://www-saiglobal-com.ezproxy.utas.edu.au/online/autologin.asp (Accessed: 2 April 2019).

Standards Australia (2010) *AS 1720.2–2006 (Incorporating Amendment No. 1): Timber structures - Part 2: Timber properties.* Available at: https://www-saiglobal-com.ezproxy.utas.edu.au/online/autologin.asp (Accessed: 2 April 2019).

Standards Australia & Standards New Zealand (1998) *AS/NZS 1328.1:1998 (Incorporating Amendment No. 1): Glued laminated structural timber Part 1: Performance requirements and minimum production requirements.* Available at: https://www-saiglobal-com.ezproxy.utas.edu.au/online/autologin.asp (Accessed: 1 April 2019).

Standards Australia & Standards New Zealand (1998) *AS/NZS 1328.2:1998: Glued laminated structural timber Part 2: Guidelines for AS/NZS 1328: Part 1 for the selection, production and installation of glued laminated structural timber*. Available at: https://www-saiglobal-com.ezproxy.utas.edu.au/online/autologin.asp (Accessed: 1 April 2019).

Standards Australia (2006) *AS 5068—2006 (Incorporating Amendment No. 1) (reconfirmed 2016): Timber—Finger joints in structural products—Production requirements.* Available at: https://www-saiglobal-com.ezproxy.utas.edu.au/online/autologin.asp (Accessed: 11 April 2019).

Standards Australia & Standards New Zealand (2010) *AS/NZS 4063.1:2010: Characterization of structural timber Part 1: Test methods.* Available at: https://www-saiglobal-com.ezproxy.utas.edu.au/online/autologin.asp (Accessed: 3 April 2019).

Standards Australia & Standards New Zealand (2010) *AS/NZS 4063.2:2010: Characterization of structural timber Part 2: Determination of characteristic values*. Available at: https://www-saiglobal-com.ezproxy.utas.edu.au/online/autologin.asp (Accessed: 3 April 2019).

Standards Australia & Standards New Zealand (2010) *AS/NZS 4364:2010: Timber—Bond performance of structural adhesives.* Available at: https://www-saiglobal-com.ezproxy.utas.edu.au/online/autologin.asp (Accessed: 3 April 2019).

5.2 European standards

EUROPEAN COMMITTEE FOR STANDARDIZATION (1995) *BS EN 386: Glued laminated timber—Performance requirements and minimum production requirements.*

EUROPEAN COMMITTEE FOR STANDARDIZATION (2013) *FprEN 14080:2013 (E) (FINAL DRAFT): Timber structures - Glued laminated timber and glued solid timber – Requirements.*

EUROPEAN COMMITTEE FOR STANDARDIZATION (2018) *WI 124xxx:2018 (IN PROGRESS): Timber structures — Hardwood glued laminated timber — Requirements.*

EUROPEAN COMMITTEE FOR STANDARDIZATION (2017) *EN 301:2017 (D): Title in English: Adhesives, phenolic and aminoplastic, for load-bearing timber structures - Classification and performance requirements.* Available at: https://su.snvhosting.ch/enorm/ (Accessed: 30 April 2019).

EUROPEAN COMMITTEE FOR STANDARDIZATION (2017 EN 15425:2017 (D): Title in English: Adhesives - One component polyurethane (PUR) for load-bearing timber structures - Classification and performance requirements. Available at: https://su.snvhosting.ch/enorm/ (Accessed: 6 May 2019).
EUROPEAN COMMITTEE FOR STANDARDIZATION (2013) *EN 302-1:2013: Adhesives for load-bearing timber structures. Test methods. Determination of longitudinal tensile shear strength.*

EUROPEAN COMMITTEE FOR STANDARDIZATION (2017) *EN 302-2:2017: Adhesives for load-bearing timber structures – Test methods - Part 2: Determination of resistance to delamination.*

EUROPEAN COMMITTEE FOR STANDARDIZATION (2017) *EN 302-3:2017: Adhesives for load-bearing timber structures – Test methods - Part 3: Determination of the effect of acid damage to wood fibres by temperature and humidity cycling on the transverse tensile strength.*

EUROPEAN COMMITTEE FOR STANDARDIZATION (2017) *EN 408:2010+A1:2012 (E): Title in English: Timber structures - Structural timber and glued laminated timber - Determination of some physical and mechanical properties.*

Sigirst, C. (2019) Email to Christophe Sigrist, 3 April.

Glue Laminated Timber

in Australian and European Standards

Albert Beeler

Edited by Dr Assaad Taoum, Dr Marcus Noh and Nikki Nolan

Glue Laminated Timber in Australian and European Building Standards

Contents

Definitions

These were sourced from the Wood Solutions Website, https://www.woodsolutions.com.au/wood-product-categories/, accessed 15th September 2020.

Glulam

Glulam, short for Glued Laminated Timber (GLT), is an engineered wood product manufactured by gluing together pieces of timber, known as laminates. This process produces a larger size and longer length members, which can be curved or straight.

Timber laminates used in the production of glulam are typically finger-jointed into continuous lengths and available in a range of both softwood and hardwood species. The thicknesses of the laminates will depend on the application and the species used. Prior to gluing, the laminations are accurately dressed to an exact and uniform thickness. The laminates will also be clamped together under constant pressure until the glue has cured. Once glued, members are planned, cut to an exact size and may be coated with a water repellent sealant.

CLT

Cross Laminated Timber (CLT) is an engineered wood product, similar in construction to extremely large plywood, used for prefabricated structural applications.

Layers of timber, known as lamellas, are glued together with the grain alternating at 90-degree angles for each layer. The exterior layers' grains run lengthways, giving optimum strength. CLT is manufactured in a similar way to glulam, except that glulam is layered with the grain.

Cross-laminating layers of wood veneer improve the structural properties of wood by distributing the along-the-grain strength of wood in both directions, and this means that CLT panels can be used to form complete floors, walls and roofs.

Fit for Purpose

When timber and wood products are sold, suppliers are bound by law to provide products that are fit for a customer's intended purpose or application. A product is fit-for-purpose if it does the job that the consumer wants or was told that it would do, for an extended period of time.

Introduction

This document provides a review and comparative analysis of the Australian and European building and product standards that relate to the glue and glue line performance in glue-laminated timber (glulam). It focuses on the potential for glulam made from plantation *Eucalyptus nitens* (*E. nitens*).

In general, European glulam production standards are more extensive than comparable Australian standards and cover more design aspects and tests. This document outlines which European glulam production tests Australian producers should consider in addition to those required in Australian Standards. Conducting these additional tests may increase the long-term credibility and the commercial potential of *E. nitens* glulam products in domestic and international markets[1].

This report will firstly provide an overview of the standards (Section A. Overview of the Standards), a summary of the review of standards (Section B. Executive Summary), then list the tests that the standards include (Section C. Important Tests). Following this, there is a case study on *E. nitens* (Section D. Case study) and then a detailed review of each standard, with screenshots provided for key formulas and test methods (Appendix 2, Detailed Analysis). It is expected that for most audiences, the first three sections (A - D) will be of most use to understand the context of standards relevant to glulam products in Australia.

A. Overview of the Standards

There are 15 Australian standards and 9 European standards that have been reviewed in part or full in this report. It is important to note that there is a European building standard in development, that deals with glulam made from hardwood species. The standard is *WI 124xxx:2018 (IN PROGRESS): Timber structures — Hardwood glued laminated timber — Requirements*, which is expected to be released in 2021.

The following table demonstrates the spread of standards that are relevant to the design, building, construction, products, tests and adhesives, for both the Australian and European contexts.

Australian	European
Umbrella standard	
NCC Vol 1 & 2 – May 2019 (*National Construction* Code) A performance-based code containing all Performance Requirements for the construction of buildings, but no constructions with glulam are covered.	
Design / building / construction	
AS 1720.1 – 2010 (*Timber structures – Design methods*) For use in the design and appraisal of structural elements or systems comprised of timber or wood products.	EN 1995 (*Eurocode 5: Design of Timber Structures*) Gives general design rules for timber structures together with specific design rules for buildings.
AS 1720.2 – 2006 (*Timber structures – Timber properties*) Sets out a table of species and their general properties, which can be used for the design of timber structures.	

[1] Regarding CLT, it is important to note, that the basic tests in the standards concerning glue and glue line are the same as for glulam (Sigrist, 2019). For this reason, the topics of glue and bonding for CLT are not investigated in this report. However, relevant considerations regarding CLT (e.g. clamping pressure limited because of the use of vacuum press), will be mentioned.

Australian	European
AS 1684.2 – 2010 (*Residential timber-framed construction – Non-cyclonic areas*) Procedures that can be used to determine building practice, to design or check construction details, and to determine member sizes, and bracing and fixing requirements for timber-frames construction in non-cyclonic areas.	
AS 1684.3 – 2010 (Residential timber-framed construction – Cyclonic areas) As per AS 1684.2 for Cyclonic areas.	
AS 1684.4 – 2010 (Residential timber-framed construction – Simplified Non-cyclonic areas) As per AS 1684.2 for Non-cyclonic areas for wind classifications N1 and N2.	
Product / Test / Adhesive	
AS 1328.1 – 1998 (Glue laminated structural timber – Performance requirements and minimum production requirements) (Based on EN 386, which has been replaced by EN 14080 – right) Covers timber quality, the strength of end-joints and face-joints between laminations, and adhesive type, which is related to Service Classes 1, 2 and 3. Based on EN 386 (now EN 14080).	EN 14080 – 2013 (Timber structures – Glued laminated timber and glued solid timber – requirements) Performance requirements of the following glued laminated products: glued laminated timber (glulam), glued solid timber, glued with large finger joints, and block glued glulam for use in buildings and bridges.
AS 1328.2 – 1998 (Glue laminated structural timber guidelines for AS 1328.1 Part 1 for the selection, production and installation of glued laminated structural timber – Withdrawn – Advice only) Provides detailed guidance for the production of glulam. A set of stress grades is given for design purposes to simplify the use and installation of graded material. Guidelines provided for quality control, third-party certification and for establishing structural properties.	WI 124xxx – 2018 In Progress (Timber structures – hardwood glued laminated timber – requirements) This European Standard sets out requirements regarding the performance of characteristics of the following types of glued laminated products made of hardwood to be used in buildings and bridges. Type 1: hardwood glued laminated timber (hardwood glulam). Type 2: hardwood block glued glulam.
Test / Adhesive	
AS 4364 – 2010 (Timber – Bond performance of structural adhesives) Provides the requirements for the bond performance of adhesives formed in structural finger-jointed timber and glulam products. Focuses on bondline performance and is directed at the evaluation of wood adhesives.	EN 301:2017 (D) (*Title in English: Adhesives, phenolic and amino plastic, for load-bearing timber structures - Classification and performance requirements*). This European Standard establishes a classification for phenolic and amino plastic polycondensation adhesives according to their suitability for use for load-bearing timber structures in defined climatic exposure conditions and specifies performance requirements for such adhesives for the factory manufacture or factory-like manufacturing conditions of load-bearing timber structures only.

Australian	**European**
AS 5068 – 2006 (Timber – Finger joints in structural products – Production Requirements) This standard is a performance-based document that applies to finger jointed hardwood and softwood, used directly with either structural timber or laminations of glued laminated timber. This standard requires producers to implement a documented production control system.	EN 15425:2017 (D) (*Title in English: Adhesives - One component polyurethane (PUR) for load-bearing timber structures - Classification and performance requirements*) This European Standard establishes a classification for one component polyurethane (PUR) adhesives according to their suitability for use in load-bearing timber structures in defined climatic exposure conditions; it specifies performance requirements for such adhesives for the factory manufacture or factory-like manufacturing of load-bearing timber structures only.
	EN 302-1:2013 (*Adhesives for load-bearing timber structures. Test methods. Determination of longitudinal tensile shear strength*). This European Standard specifies a method for determining the shear strength of adhesive bonds in close contact glue line and thick glue line. It is suitable for the following applications: a) assessing the compliance of adhesives with EN 301, EN 15425 and prEN 16254; b) assessing the suitability and quality of adhesives for load-bearing timber structures.
AS 4063.2 – 2010 (Characterisation of structural timber. Part 2: Determination of characteristic values) This Standard is to provide requirements for the sampling, statistical evaluation of test data and the determination of design characteristic values for structural timber for structural design in accordance with the relevant Australian or New Zealand timber engineering design standard.	EN 302-2:2017 (*Adhesives for load-bearing timber structures – Test methods - Part 2: Determination of resistance to delamination*). This European Standard specifies a method for determining the resistance to delamination in glue lines. As per EN 302-1 above, plus: c) comparing the effects on the bond strength resulting from the choice of bonding conditions, from different climatic conditioning and from the treatment of the test pieces before and after bonding.
	EN 302-3:2017 (*Adhesives for load-bearing timber structures – Test methods - Part 3: Determination of the effect of acid damage to wood fibres by temperature and humidity cycling on the transverse tensile strength*). This European Standard specifies a method for determining the effect on bond strength of damage to wood fibres caused by the action of acids from the adhesive or primer used in the gluing process during climatic cycling. It is suitable for the following applications: As per a) and b) in EN 302-1 & 2 above, plus: c) determining if the adhesive after bonding has a damaging influence on the strength of the wood due to chemical action.

Australian	European
AS 4063.1 – 2010 (Characterisation of structural timber. Part 1: Test methods) (This is equivalent to EN408 – right). This Standard specifies requirements for testing rectangular sections of sawn solid timber of commercial structural size to provide data for the determination of characteristic values for structural design. It specifies the test methods only.	EN 408:2010+A1:2012 (E) (*Title in English: Timber structures - Structural timber and glued laminated timber - Determination of some physical and mechanical properties*). This European Standard specifies test methods for determining the following properties of structural timber and glued laminated timber: modulus of elasticity in bending; shear modulus; bending strength, modulus of elasticity in tension and tension strength parallel to the grain; modulus of elasticity in compression and compression strength parallel to the grain; modulus of elasticity in tension and tension strength perpendicular to the grain; modulus of elasticity in compression and compression strength perpendicular to the grain; and shear strength.

B. Executive Summary

The Australian standard for glulam production is '*AS 1328.1 – Glue Laminated Structural Timber*', and the European standard is '*EN 14080 – Timber structures – Glued laminated timber and glued solid timber*'. The Australian standard does not have any restrictions regarding plantation wood species. The European standard covers softwoods and poplar timber species.

Although hardwood is not specifically covered in EN 14080 (apart from poplar), this standard provides an overview of the various tests that would need to be performed on plantation hardwood to ensure reliable bonding in glulam. A specific European standard for hardwood glulam, WI 124xxx 2018, is still in development. This new standard will provide hardwood specific requirements and tests. This report has reviewed the draft of WI 124xxx 2018, and many elements in this new standard are similar to EN 14080. The final version is expected to be published in 2021.

Several Australian standards relevant to glulam have been developed directly from the European standards of the same topic (these are noted in the overview above). Both Australian and European standards are generally similar in initial and factory production control tests (also called routine tests) for glulam.

Some examples of similarities between the AS and EN standards include:

- Requirements for shear strength and delamination resistance in AS 4364 that can be tested according to EN 302-1 and EN 302-2.
- Finger joint strength can be tested with a bending test for both AS and EN standards.
- Full-scale bending tests are described to test the glulam for both AS and EN standards.

In addition to these similarities, there are also differences:

- EN 14080 refers to more tests than AS 1328.1 and AS/NZS 4364 generally.
- With regard to full-scale bending tests mentioned above, in AS 1328.1 the standard depth of the beam is 300mm, whereas in EN 14080 it is 600mm.
- EN 14080 includes PUR adhesive requirements not mentioned in AS 1328.1 (AS 1328.1 is based on the outdated standard BS EN 385:1995). In EN 14080 this important topic is well covered via EN 15425 where many detailed tests are listed.
- EN 301 is relevant to phenolic or aminoplastic adhesives and EN 15425 is relevant to PUR adhesives and provides more specific tests. Note: many of these tests are detailed and only concern high-level glue producers.
- In AS 5068, for glulam in service class 2 and 3, a wet test for the finger joints is required for bending or tension test, while in the European standards all finger joint-related tests are carried out in dry conditions.

In summary, the European standard EN 14080 covers more aspects of gluing for glulam products than the equivalent Australian Standard. European standards for timber products are globally better known and accepted than the Australian Standards counterparts. In this period of time before the European hardwood glulam standard is available, it would be advantageous to follow the test procedures outlined in the European standards in addition to the Australian Standards.

C. Important Tests

The following section of this report identifies the important tests identified from each standard. This test information is subsequently applied in ‘Section D. Case study’ to *Eucalyptus nitens* and the tests required for glulam development of this plantation species.

Australian Standards					
No.	**Required by[2]**	**Test // according to // (description)**	**Initial test or routine**	**Frequency[3] and sample number**	**Comments**
1	AS/NZS 1328.1, pg. 8 (hereafter AS 1328.1)	Bending test MOE and MOR // AS/NZS 4063 // on completed 300mm deep glulam members	Initial	One glulam member (AS 1328.1, pg. 9)	Characteristics could also be determined from lamination properties (method 2, AS 1328.1, pg.9)
2	AS 1328.1, pg. 11	Delamination test (if methods A, B or C depends on various factors see table 2.1 AS 1328.1) // AS 1328.1 Appendix C // on full manufactured glulam cross sections 75mm long	Initial	Min. 5 samples (AS 1328.1, pg.10)	
3	AS 1328.1, pg. 11	Delamination test with method C (for service class 1 and 2) // AS 1328.1 Appendix C // on full manufactured glulam cross-section 75mm long	Routine	1 sample for each shift, for each press lead, or, every $10m^3$ of production (AS 1328.1, pg.10)	For this routine test, either the delamination test (method C, Appendix C) OR the block shear test has to be made (for service class 1 and 2)
4	AS 1328.1, pg. 11	Block shear test // AS 1328.1 Appendix D // from a full manufactured glulam cross-section 40-50 mm long	Routine	1 sample for each shift, for each press lead, or, every $10m^3$ of production (AS 1328.1, pg.10) Frequency can be reduced if after 3 months all tests are satisfying conditions, see AS/NZS 1328.1, pg. 17	

[2] For issue and title of the standard, refer to the Overview of Standards section.

[3] For the frequency for initial tests, they are performed just one time in the beginning in the case of new wood species, glue, production parameter.

Australian Standards					
5	AS 1328.1, pg. 9	Stress assessment on joints in bending // AS 5068, pg. 7 & 10 // bending strength	Routine	Method a) each finger joint from a sample taken from a production batch Method b) at least 15 finger joints tested from the same production line	AS 5068, pg. 10: Tension strength could be tested instead of bending strength. Described on the same pages as the bending tests // AS 1328.1, pg. 17: Instead of sample testing, the verification can also be done by proof testing.
6	AS/NZS 4364, pg. 8 & 9. (hereafter AS 4364)	Adhesive bond durability for service class 2 & 3 // AS 5068, pg. 11 and Appendix B // bending with wet specimen	Routine	One sample of at least four joints per month from production, at a rate of one specimen per week (AS 5068, pg. 11)	AS 5068, pg. 11: Instead of bending the test could also be made on tension.
7	AS 4364, pg. 8 & 9, (to AS 4364 is referred to in AS 1328.1, pg. 2, 8 & 15)	Shear strength and wood failure // EN 301, EN 302-1 // shear test on samples made specifically for the test	Initial	No information about sample number, because EN 302-1 could not be procured	(This test is primarily about the glue)
8	AS 4364, pg. 9 (to AS 4364 is referred to in AS 1328.1, pg. 2, 8 & 15)	Delamination resistance // EN 301, EN 302-2 // delamination test on samples made specifically for the test	Initial	Samples 75 x ca. 150 x ca. 150mm: Four with minimum and four with maximum closed assembly time (EN 302-2, pg. 7)	(This test is primarily about the glue)

European Standards					
No.	**Required by[2]**	**Test // according to // (description)**	**Initial test or routine**	**Frequency[3] and sample number**	**Comments**
9	EN 14080, pg. 18, 19, 26, 43	MOE and MOR test glulam // EN 14080 Annex F, EN 408 //full-scale test (standard depth 600mm)	Initial	30 glulam specimens (EN 14080, pg. 43)	Instead of full-scale tests, the verification could also be made by classifications from layups and lamination properties or from cross-sectional layups (EN 14080, pg. 18)
10	EN 14080, pg. 26, 42 & 44	Strength of finger joints in lamination by bending // EN 14080 Annex E, EN 408 // test of the whole jointed cross-section of the lamination	Initial	Depending on the circumstances (EN 14080, pg. 42 & 43) either 15, 30 or 100 finger joints in lamination	

European Standards					
11	EN 14080, pg. 26 & 50	Strength of finger joints in laminations be bending // EN 14080 Annex E, EN 408 // test of the whole jointed cross-section of the lamination	Routine	At least 3 per shift and line, highest strength class or manufacturer specific strength class and adhesive (EN 14080 pg. 50)	Under certain circumstances, instead of bending tests, tension tests can be made which have to be carried out according to EN 14080, Annex E
12	EN 14080, pg. 34 & 44	Delamination test // EN 14080 Annex C // cross sections 75mm long cut from manufactured glulam	Initial	10 full cross-sectional specimens	Under certain circumstances smaller size than full cross sections are possible, see EN 14080, pg. 64
13	EN 14080, pg. 34 & 50	Delamination test // EN 14080 Annex C, Method A, B or C // cross-sections 75mm long cut from manufactured glulam	Routine	One full cross-sectional specimen for each 20m^3 of production or part thereof (reduction of the number of samples possible under certain circumstances), see EN 14080, pg. 50 note	For factory production control either this delamination test has to be conducted OR the shear strength test below, number 14)
14	EN 14080, pg. 34 & 50	Shear strength of glue lines // EN 14080 Annex D // cross-sections 75mm long cut from manufactured glulam	Routine	One full cross-sectional specimen for each 20m3 of production or part thereof (reduction of the number of samples possible under certain circumstances), see EN 14080, pg. 50 note	For factory production control either this shear strength test has to be conducted OR the delamination test above, number 13)
15	EN 14080, pg. 34 & 50	Shear strength // EN 301 respectively EN 15425, EN 302-1 // shear test on samples made specifically for that test	Initial	No information about sample number because EN 302-1 could not be procured	
16	EN 14080, pg. 34 & 50	Delamination resistance // EN 301 respectively EN 15425, EN 302-2 // Delamination test on samples made specifically for the test	Initial	Samples 75 x ca. 150 x ca. 150mm: Four with minimum and four with maximum closed assembly time (EN 302-2, pg. 7)	

European Standards					
17	EN 14080, pg. 34 & 50	Creep test (long-term load at cyclic climate conditions) // EN 14080 Annex B.2 // samples ca. 50 x 50 x 50mm made specifically for the test and tests last up to 12 months	Initial	80 samples	This test only applied for PUR and EPI, NOT for phenolic and amino plastic adhesives
18	WD W1 124xxx, pg. 20	Wet shear test // WD W1 124xxx, pg. 20 Annex F // shear test in wet conditions	Routine	One full cross-sectional specimen for each 20m3 of production or part thereof	Standard still in development. It is possible requirements could change.

D. Case study

Eucalyptus nitens

The following case study is a review of the tests mentioned in both the AS and EN standards with respect to developing *Eucalyptus nitens* glulam members in the Tasmanian context. As noted in the Executive Summary above, the standard for glulam produced from hardwood timber species is still in development in Europe and will impact the development of *E. nitens* glulam when published.

The context for this case study is the NIFPI research project '*NIF080 Developing laminated structural elements from fibre-managed plantation hardwood*', to be published in 2021, which includes a research collaboration between the University of Tasmania's Centre for the Sustainable Architecture with Wood (CSAW) and the Bern University of Applied Sciences in Biel, Switzerland. Where glulam production tests may not be available at UTAS due to equipment or cost-effectiveness, there is the option of testing glulam at Bern University.

As mentioned in section B. Executive Summary, there are some aspects of the glulam process not currently covered by Australian Standards. For this reason, it is recommended that tests are predominantly conducted according to the European standards where possible. Two advantages of this with regard to the potential future international commercialisation of *E. nitens* glulam are:

- Glulam developed according to the European standards will have more currency in the international market, as European standards for timber products are globally better known and accepted than the Australian counterparts.
- It will also retain currency for a longer time than the Australian standards, given that the recently updated European standards are closely aligned with and relevant to the new European standard for hardwood glulam which is due to be released in 2021.

A summary of the tests indicates material testing can be divided into two phases:

Test Phases	
Phase 1	• Most relevant tests will be conducted with a small sample number. • Tests that can be done quickly at any available test facilities will be performed first. • Preferably the test can be performed with the samples cut from the glulam or the whole glulam beam for full-scale tests produced by the industrial partner(s) or the finger joints from laminations. The tested finger joints should be produced industrially. • The goal of Phase 1 is to evaluate the potential of the glulam with plantation *E. nitens*, to get an idea about the material, glue and bonding, and to identify possible pitfalls and difficulties.
Phase 2	• Same tests as in phase 1 will be performed, but with more sample numbers. If necessary, optimised parameters such as pressing time and adapted glue could be considered. • If the samples cannot be cut from the glulam, a further test should be made specifically. • The goal of Phase 2 is to statistically and technically verify the results from phase 1, bringing the glulam closer in line with the standards through more tests and fine-tuning of process parameters.

This two-phase approach provides expedited initial results which then determine how to proceed. According to this standard review regarding the topics of glue, bonding and bending tests, for Phase 1 the following tests could be included:

Phase 1 Tests	
Glue and bonding:	• Delamination test either according to AS 1328.1 Appendix C or EN 14080 Annex C • Shear test either according to AS 1328.1 Appendix D or EN 14080 Annex D
Finger joints	• Test of finger joint strength with bending test according to AS 1328.1/ AS 5068 or EN 14080). The finger joints sample should be produced industrially. • It should be determined if the wet test as per AS 5068 is appropriate.

Bending tests	• Full-scale tests at UTAS on glulam beams produced by the industry partner(s) will be performed. Possibly the depth of the beams should be greater than 300mm and with ideally 15 laminations. The bigger the beam is, the closer the test is to the depth requirements of the European standard test beam which is 600mm deep. Consider hereby EN 408, where the span can be 15h instead of 18h. • Test of finger joint strength

Regarding the glue system, it is likely production will be undertaken with only one glue system that is most commonly used by the industry, such as PUR adhesive. If possible, the second most common adhesives, such as phenolic or aminoplastic adhesives (MF, MUF, PRF, UF), would be an interesting comparison and would provide a broader idea about glue systems.

In view of future CLT made of plantation *E. nitens*, face gluing of *E. nitens* glulam in the above tests could also include some samples at the same clamping pressure as with the vacuum press, and some at a higher clamping pressure. This would then provide an interesting comparison regarding the influence of the pressure on bonding performance and glue line thickness.

Regarding equipment, it would be optimal if delamination tests can be made by the industrial partner or by UTAS. For the bending test, testing bigger beams would be preferable. If large-size beams are too costly, the tests can be done at the Bern University in Biel, Switzerland.

Which tests should be made in Phase 2 depends significantly on the results of the initial tests in Phase 1. Phase 2 tests should include the same tests as in Phase 1, but with more samples to verify the Phase 1 results statistically. The following tests are suggested as a guideline:

Phase 2 Tests	
Glue and bonding:	• Delamination test according to EN 302-2 as an initial test with the samples made specifically for the test. (recommended equipment is an autoclave or other devices that allow delamination tests such as partial vacuum and overpressure) • Shear test according to EN 302-1 as an initial test with the samples made specifically for the test • Long-term sustained load test at cyclic climate conditions according to EN 14080 Annex B.2 • In case the glue producer is not able to recommend the specific minimal pressing time, it has to be discussed if tests shall be made to determine the pressing time according to the standards EN 302-6 or EN 15416-5. Otherwise, a simple test can be developed. • There is a wide range of further tests referred to in EN 14080 in which the tests are referred to in standards EN 301 and EN 15425. It has to be discussed at that stage whether some of these shall be tested or not[4]
Finger joints	• Apart from the tests on bending in Phase 1, also tests regarding tension should be performed according to AS 1328.1/ AS 5068 or EN 14080. As Phase 1, the finger joints should be produced industrially
Bending tests	• The samples for the full-scale glulam tests in Phase 2 should definitively be deeper than 300mm, e.g., 450mm or even 600mm deep. This could be done in Biel, Switzerland if it is not possible at UTAS. As per EN 408, the span can be 15h instead of 18h

[4] For these many and often very detailed tests, it is important to involve the glue producer if possible. It would be ideal if the producer can do some of these tests with *E. nitens* and the glue envisaged. Also, it would be helpful if the producer makes these tests using other hardwood species since this could be a useful indication for how the glue would perform on *E. nitens*.

Appendix 1

List of Australian Standards

Australian Standards

Australian Building Codes Board (2019) *NCC 2019 Building Code of Australia - Volume One.* Available at: https://ncc.abcb.gov.au/ncc-online/NCC (Accessed: 1 May 2019).

Australian Building Codes Board (2019) *NCC 2019 Building Code of Australia - Volume Two.* Available at: https://ncc.abcb.gov.au/ncc-online/NCC (Accessed: 1 May 2019).

Australian Building Codes Board (2019) *NCC 2019 Building Code of Australia - Volume Three.* Available at: https://ncc.abcb.gov.au/ncc-online/NCC (Accessed: 1 May 2019).

Australian Building Codes Board (2019) *NCC 2019 Guide to BCA Volume One.* Available at: https://ncc.abcb.gov.au/ncc-online/NCC (Accessed: 1 May 2019).

Standards Australia (2010) *AS 1684.2 — 2010 (Incorporating Amendment Nos 1 and 2): Residential timber-framed construction - Part 2: Non-Cyclonic Areas.* Available at: https://www-saiglobal-com.ezproxy.utas.edu.au/online/autologin.asp (Accessed: 3 April 2019).

Standards Australia (2010) *AS 1684.3 — 2010 (Incorporating Amendment No. 1): Residential timber-framed construction - Part 3: Cyclonic Areas.* Available at: https://www-saiglobal-com.ezproxy.utas.edu.au/online/autologin.asp (Accessed: 3 April 2019).

Standards Australia (2010) AS 1684.4 — 2010 (Incorporating Amendment No. 1): Residential timber-framed construction - Part 4: Simplified—Non-Cyclonic Areas. Available at: https://www-saiglobal-com.ezproxy.utas.edu.au/online/autologin.asp (Accessed: 3 April 2019).

Standards Australia (2010) *AS 1720.1–2010 (Incorporating Amendment Nos 1, 2 and 3): Timber structures - Part 1: Design methods.* Available at: https://www-saiglobal-com.ezproxy.utas.edu.au/online/autologin.asp (Accessed: 2 April 2019).

Standards Australia (2010) *AS 1720.2–2006 (Incorporating Amendment No. 1): Timber structures - Part 2: Timber properties.* Available at: https://www-saiglobal-com.ezproxy.utas.edu.au/online/autologin.asp (Accessed: 2 April 2019).

Standards Australia & Standards New Zealand (1998) AS/NZS 1328.1:1998 (Incorporating Amendment No. 1): Glued laminated structural timber Part 1: Performance requirements and minimum production requirements. Available at: https://www-saiglobal-com.ezproxy.utas.edu.au/online/autologin.asp (Accessed: 1 April 2019).

Standards Australia & Standards New Zealand (1998) AS/NZS 1328.2:1998: Glued laminated structural timber Part 2: Guidelines for AS/NZS 1328: Part 1 for the selection, production and installation of glued laminated structural timber. Available at: https://www-saiglobal-com.ezproxy.utas.edu.au/online/autologin.asp (Accessed: 1 April 2019).

Standards Australia (2006) AS 5068—2006 (Incorporating Amendment No. 1) (reconfirmed 2016): Timber—Finger joints in structural products—Production requirements. Available at: https://www-saiglobal-com.ezproxy.utas.edu.au/online/autologin.asp (Accessed: 11 April 2019).

Standards Australia & Standards New Zealand (2010) *AS/NZS 4063.1Characterisationization of structural timber Part 1: Test methods.* Available at: https://www-saiglobal-com.ezproxy.utas.edu.au/online/autologin.asp (Accessed: 3 April 2019).

Standards Australia & Standards New Zealand (2010) *AS/NZS 4063.2Characterisationization of structural timber Part 2: Determination of characteristic values.* Available at: https://www-saiglobal-com.ezproxy.utas.edu.au/online/autologin.asp (Accessed: 3 April 2019).

Standards Australia & Standards New Zealand (2010) *AS/NZS 4364:2010: Timber—Bond performance of structural adhesives.* Available at: https://www-saiglobal-com.ezproxy.utas.edu.au/online/autologin.asp (Accessed: 3 April 2019).

List of Europeans Standards

EUROPEAN COMMITTSTANDARDISATIONIZATION (1995) BS EN 386: Glued laminated timber— Performance requirements and minimum production requirements.

EUROPEAN COMMITTSTANDARDISATIONIZATION (2013) FprEN 14080:2013 (E) (FINAL DRAFT): Timber structures - Glued laminated timber and glued solid timber – Requirements.

EUROPEAN COMMITTSTANDARDISATIONIZATION (2018) WI 124xxx:2018 (IN PROGRESS): Timber structures — Hardwood glued laminated timber — Requirements.

EUROPEAN COMMITTSTANDARDISATIONIZATION (2017) EN 301:2017 (D): Title in English: Adhesives, phenolic and aminoplastic, for load-bearing timber structures - Classification and performance requirements. Available at: https://su.snvhosting.ch/enorm/ (Accessed: 30 April 2019).

EUROPEAN COMMITTSTANDARDISATIONIZATION (2017 EN 15425:2017 (D): Title in English: Adhesives - One component polyurethane (PUR) for load-bearing timber structures - Classification and performance requirements. Available at: https://su.snvhosting.ch/enorm/ (Accessed: 6 May 2019).

EUROPEAN COMMITTSTANDARDISATIONIZATION (2013) EN 302-1:2013: Adhesives for load-bearing timber structures. Test methods. Determination of longitudinal tensile shear strength.

EUROPEAN COMMITTSTANDARDISATIONIZATION (2017) EN 302-2:2017: Adhesives for load-bearing timber structures – Test methods - Part 2: Determination of resistance to delamination.

EUROPEAN COMMITTSTANDARDISATIONIZATION (2017) EN 302-3:2017: Adhesives for load-bearing timber structures – Test methods - Part 3: Determination of the effect of acid damage to wood fibres by temperature and humidity cycling on the transverse tensile strength.

EUROPEAN COMMITTSTANDARDISATIONIZATION (2017) EN 408:2010+A1:2012 (E): Title in English: Timber structures - Structural timber and glued laminated timber - Determination of some physical and mechanical properties.

Appendix 2

Detailed Analysis

NCC – National Construction Code 2019, Building Code of Australia Vol 1 & 2

Description:

"The National Construction Code (NCC) provides the minimum requirements for safety and health; amenity and accessibility, and sustainability in the design, construction, performance and liveability of new buildings (and new building work in existing buildings) throughout Australia. It is a uniform set of technical provisions for building work and plumbing and drainage installations throughout Australia that allows for variations in climate and geological or geographic conditions".

Source: www.ncc.abcb.gov.au/ncc-online, accessed: 20th October 2020.

Conditions:

The documents included in the NCC 2019 Complete series are NCC 2019 Complete Series Volumes One, Two, Three and the Guide to Volume One. Vol 1 and 2.

Components of the NCC

The NCC provides the technical provisions for the design and construction of buildings and other structures, and plumbing and drainage systems.

NCC Volume One primarily covers the design and construction of multi-residential, commercial, industrial and public assembly buildings and some associated structures.

NCC Volume Two primarily covers the design and construction of smaller scale buildings including houses, small sheds, carports and some associated structures.

NCC Volume Three covers the design, construction and maintenance of plumbing and drainage systems in new and existing buildings.

Figure 1: NCC 2019 Building Code of Australia Vol 1, pg. 8

Topics not considered within the context of glulam for this report:

- Termites
- Fire resistance
- State-relevant requirements (for instance durability Queensland)

Relevant findings:

NCC Vol 1 is relevant for all Class 2 to 9 buildings (multi-residential, commercial, industrial and public assembly buildings and associated structures).

About NCC Volume One

NCC Volume One contains technical design and construction requirements for all Class 2 to 9 buildings (multi-residential, commercial, industrial, and public assembly buildings) and their associated structures.

NCC Volume One contains the requirements for—

- all Class 2 to 9 buildings; and
- access requirements for people with a disability in Class 1b and 10a buildings; and
- certain Class 10b structures including access requirements for people with a disability in Class 10b *swimming pools*.

Figure 2: NCC 2019 Building Code of Australia Vol 1, pg. 10

NCC Vol 1 identifies the relevant standards for timber construction (marked in blue):

(f) Timber construction:

(i) Design of timber structures: AS 1720.1.

(ii) * * * * *

(iii) Timber structures: AS 1684.2, AS 1684.3 or AS 1684.4.

(iv) Nailplated timber roof trusses: AS 1720.5.

Figure 3: NCC 2019 Building Code of Australia Vol 1, pg. 52

NCC Vol 2 is relevant for Class 1 and 10 buildings (certain residential and non-habitable buildings and structures).

About NCC Volume Two

NCC Volume Two contains technical design and construction requirements for certain residential and non-habitable buildings and structures.

Volume Two contains the requirements for—

- Class 1 and 10a buildings (other than access requirements for people with a disability in Class 1b and 10a buildings); and
- certain Class 10b structures (other than access requirements for people with a disability in Class 10b *swimming pools*); and
- Class 10c *private bushfire shelters*.

Figure 4: NCC 2019 Building Code of Australia Vol 2, pg. 9

NCC Vol 2 identifies the relevant standards for timber construction (marked in blue):

3.4.3.0

Performance Requirement P2.1.1 is satisfied for a timber frame if it is designed and constructed in accordance with the following, as appropriate:

(a) Design of timber structures: AS 1720.1.

(b) Design of nailplated timber roof trusses: AS 1720.5.

(c) Residential timber-framed construction – non-cyclonic areas: AS 1684.2.

(d) Residential timber-framed construction – cyclonic areas: AS 1684.3.

(e) Residential timber-framed construction – non-cyclonic areas (simplified): AS 1684.4.

(f) Installation of particleboard flooring: AS 1860.2.

Figure 5: NCC 2019 Building Code of Australia Vol 2, pg. 159

Conclusion:

The relevant standards for timber structures as shown in the NCC 2019 Complete Series are:

- AS 1720.1
- 1684.2, 1684.3 or 1684.4

AS 1720.1 – 2010: Timber structures Part 1: Design methods

Description:

"The objective of this standard is to provide a code of practice for the design and acceptance of timber structures and elements. It includes design methods and design data appropriate for commonly encountered structural elements and materials and requirements to be met for the specification of the design, installation and maintenance of timber structures".

Source: AS 1720.1, pg. 2, accessed: 20th October 2020.

Conditions:

Australian Standard AS 1720.1—2010 and amendments No.1 and 2 were considered.

Relevant findings:

- Content covers the structural aspects of buildings
- No information about CLT included
- No explicit information about which wood species are covered (softwoods and hardwoods are mentioned throughout the standard)
- No limitations regarding plantation hardwood were found
- This standard is relevant to glulam AS 1328.1, as per Figure 6, below.

7.1 GENERAL

This Section shall be applied in conjunction with Sections 2 and 3. The provisions of this Section apply specifically to glued-laminated timber members manufactured in accordance with AS/NZS 1328.1.

Additional design methods, including methods for taper-cut and curved beams, are contained in Appendix E.

Where any glued-laminated timber is likely to be exposed to water or to damp conditions, the glued laminated timber shall be bonded with Type I adhesive specified in accordance with AS/NZS 1328.1.

Figure 6: AS/NZS 1720.1, pg. 93

Section 7 of AS 1720.1, as shown above, is relevant to the structural and design properties of glue-laminated timber, including characteristic values for strength and stiffness properties, and modification factors. The design of joints using glue-laminated timber should be in accordance with Section 4 (Design Capacity of Joints in Timber Structures). Section 2 is relevant to the Design Properties of Structural Timber Elements and Section 3 is the Design Capacity of Basic Structural Members.

Various information on roughly 40 timber species commonly used in Australia is given in AS/NZS 1720.2:

APPENDIX G

MISCELLANEOUS DESIGN INFORMATION

(Informative)

G1 ADDITIONAL INFORMATION

Basic design properties and additional design information on roughly 40 species commonly used in Australia are given in AS/NZS 1720.2.

Figure 7: AS/NZS 1720.1, pg. 153

Conclusion:

AS 1720.1 is relevant to glulam production, as it relates to AS 1328.1.

AS 1684 Residential timber-framed construction

Description:

"AS 1684.1: The objective of this standard is to provide users with the design methods, assumptions and other design criteria, which have been used in the preparation of the Span Tables, uplift forces and racking pressures contained within AS 1684.2, AS 1684.3 and AS 1684.4.

AS 1684.2: Procedures that can be used to determine building practice, to design or check construction details, and to determine member sizes, and bracing and fixing requirements for timber-frames construction in non-cyclonic areas. AS 1684.3: As per AS 1684.2 for Cyclonic areas. AS 1684.4: As per AS 1684.2 for Non-cyclonic areas for wind classifications N1 and N2".

Source: AS 1684.1, pg. 2, accessed: 20th October 2020.

Conditions:

This standard consists of four parts (see AS 1684.1-1999 Residential timber-framed construction, page 3):

AS 1684.1 Part 1: Design criteria

AS 1684.2 Part 2: Non-cyclonic area

AS 1684.3 Part 3: Cyclonic area

AS 1684.2 Part 4: Simplified-Non-cyclonic area.

The numerous supplements regarding wind classification were not considered.

Relevant findings:

- No explicit information about wood species are covered (softwoods and hardwoods are mentioned)
- No limitations regarding (plantation) hardwood found

Engineered Timber Products, including glue-laminated timber, can be used where their design is in accordance with AS 1720.1, as per Figure 8, below (this is also reflected in AS 1684.3 and .4).

1.12 ENGINEERED TIMBER PRODUCTS AND ENGINEERED WOOD PRODUCTS (EWPs)

Fabricated components (e.g., roof trusses, glued-laminated timber members, I-beams, laminated veneer lumber, laminated strand lumber and nailplate-joined timber) may be used where their design is in accordance with AS 1720.1 and their manufacture and use complies with the relevant Australian Standards.

Glued-laminated timber, I-beams, laminated veneer lumber (LVL) and laminated strand lumber (LSL) are also commonly referred to as EWPs (engineered wood products).

Figure 8: AS 1684.2 - 2010, pg. 16

No specific information about CLT is found, but non-standardised EWPs are achievable with the conditions listed below in Figure 9.

2 In some situations, there are no relevant Australian Standards applicable to the design, manufacture or use of engineered timber products. In such cases, the use of these products in accordance with this Standard is subject to the approval of the regulatory authority and the recommendations of the specific manufacturer, who may require provisions additional to those contained in this Standard. These may include, but are not restricted to, additional support, lateral restraint, blocking, and similar provisions.

Figure 9: AS 1684.2 - 2010, pg. 17

Conclusion

AS 1684 is an umbrella Design/Construction standard and is relevant to glulam through its reference to AS 1720.1 and AS 1328.1.

AS 1328.1 – 1998: Glued laminated structural timber - Performance requirements and minimum production requirements

Description:

"This standard specifies performance requirements for glued laminated timber members for structural use, and the minimum requirements for the production of such members. It is based on performance-based BS EN 386: 1995 *Glued laminated timber – performance requirements and minimum production requirements* which has been amended only where necessary to comply with Australian and New Zealand requirements".

Source: AS 1328.1 – 1998, pg. 2, accessed 22nd October 2020.

Relevant Findings:

AS 1328.1 specifies the performance requirements for glued laminated timber members for structural use, and the minimum requirements for the production of such members.

Key points about the standard include:

- It is based on the now outdated BS EN 385:1995. EN 14080, the current European standard for glulam replaced this BS standard. EN 14080 is discussed below.
- PUR glue is not mentioned in the standard.

- The standard is a generic document for hardwood and softwoods. As it sets no limits on species, it covers plantation *E. nitens*.
- AS/NZS 4364 defines the requirements for the adhesives. However, AS/NZS 4364 is mainly relevant to glue producers. See AS 1328.1 - 1998, pg. 2.

The standard defines three service classes: Service Class 1 to 3 (see Figure 10). Of these, only Service Class 1 and 2 are relevant for plantation *E. nitens* glulam products. The material does not have the durability for Service Class 3 applications.

1.3.10 Service Class 1

Service Class characterized by a moisture content in the materials corresponding to a temperature of 20°C and relative humidity of the surrounding air only exceeding 65% for a few weeks per year. (See Appendix A).

NOTE: In Service Class 1 the average equilibrium moisture content in most glulam will not exceed 12%.

1.3.11 Service Class 2

Service Class characterized by a moisture content in the materials corresponding to a temperature of 20°C and relative humidity of the surrounding air only exceeding 85% for a few weeks per year. (See Appendix A).

NOTE: In Service Class 2 the average equilibrium moisture content in most softwoods will not exceed 20%.

1.3.12 Service Class 3

Service Class characterized by climatic conditions leading to higher moisture contents than Service Class 2, or where timber is directly exposed to sun and/or rain. (See Appendix A).

Figure 10: AS 1328.1 - 1998, pg. 7

As shown in Figure 12, Section 2.4.3 presents two initial qualification tests of completed glulam:

- Method 1: Testing a 300mm deep glulam
- Method 2: Calculating the bending strength *f'*.

As this report focuses on gluing and adhesive, the characteristic tension and shear strengths in Section 2.4.3 are not discussed further. Characteristic bending strength and modulus of elasticity in bending are discussed in the 'D. Case study' section in the context of the bending-test machine at UTAS.

As shown in Figure 13, Table 2.1 lists required tests by production stage, service class and adhesive types. The production stages are Qualification (or initial) tests and Routine (or regular quality control) tests.

The number of specimens and the frequency of required test depends on the production stage (Qualification or Routine).

Delamination tests A, B and C shown in Table 2.2 in Figure 14 all involve applying a partial vacuum followed by over-pressure (with water) and drying of the wood in varied conditions. The tests differ in terms of the time, pressure, drying conditions, and the number of cycles required.

The size of the delamination test sample is consistent for each test and samples are recovered from glulam production (see Figure 11). Samples are not specially assembled pieces. The samples are similar to those required in the three delamination test methods in EN 14080 Annex C.

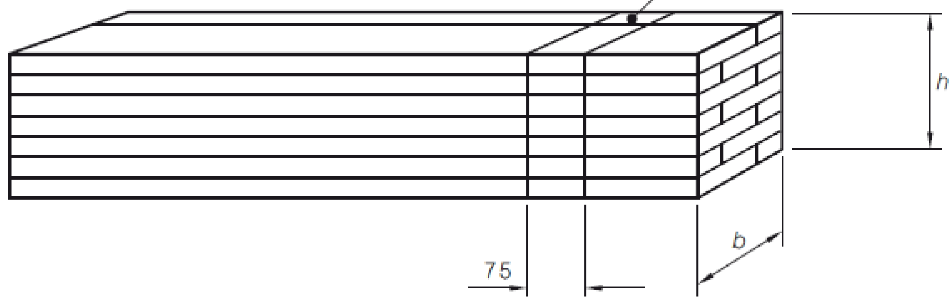


FIGURE C1 TEST SPECIMEN CUT FROM A GLULAM MEMBER

Figure 11: AS 1328.1 - 1998, Figure C.1

2.4.3 Initial qualification tests

Qualification tests shall be undertaken whenever a new process or process change involving, for example, a new adhesive/species combination, finger joint profile, lamination thickness or similar. Initial qualification tests shall be carried out either by Method 1 of Clause 2.4.3.1 or Method 2 of Clause 2.4.3.2.

2.4.3.1 *Method 1*

Determination from tests on completed glulam The characteristic strength of a glulam member in bending compression, tension and shear and characteristic modulus of elasticity in bending, shall be determined by undertaking tests on completed 300 mm deep glulam members in accordance with the AS/NZS 4063 series.

see p. 5: standard title:
Characterization of structural timber (all Parts)

2.4.3.2 *Method 2*

Determination from lamination properties The following shall apply:

(a) The characteristic strengths of a 300 mm deep horizontally laminated glulam member in bending and tension shall be computed using equations 1 and 2.

$$f'_{b} = 0.75\,(1 + 0.05\,S_{min})\; f'_{b,ej} \leq f'_{b,stock} \qquad \ldots (1)$$

$$f'_{t} = 0.75\,(1 + 0.05\,S_{min})\; f'_{t,ej} \leq f'_{t,stock} \qquad \ldots (2)$$

where

$f'_{b,ej}$ = characteristic bending strength of the finger joints in flatwise bending determined in accordance with AS 5068

$f'_{b,stock}$ = characteristic bending strength of the selected grade of lamination stock

$f'_{t,ej}$ = characteristic tension strength of the finger joints determined in accordance with AS 5068

$f'_{t,stock}$ = characteristic tension strength of lamination stock of the selected grade of the lamination stock

S_{min} = minimum spacing of end joints (m)

(b) The modulus of elasticity shall be determined by bending of lamination stock about the minor axis in accordance with the provisions of the AS/NZS 4063 series. The characteristic value of the modulus of elasticity so determined shall be deemed to apply to the laminations within the glued laminated member. The effective stiffness properties shall be determined using composite beam theory.

(c) Where manufacturers use timber, graded in accordance with the relevant grading standard for which in-grade test data are available, the values of $f'_{s,stock}$, $f'_{c,stock}$ and E_{stock} may be deemed to apply.

Figure 12: AS 1328.1 - 1998

TABLE 2.1

QUALIFICATION AND ROUTINE TEST PROCEDURES

Service	Class 1		Class 2		Class 3
Qualification test	**Type I adhesive**	**Type II adhesive**	**Type I adhesive**	**Type II adhesive**	**Type I adhesive only**
	Delamination test method A Appendix C	Delamination test method C Appendix C	Delamination test method A Appendix C	Delamination test method C Appendix C	Delamination test method A Appendix C
Routine tests	**Type I and Type II adhesives**		**Type I and Type II adhesives**		**Type I adhesives only**
	Delamination test method C Appendix C OR Block shear Appendix D OR Dry cleavage Appendix B		Delamination test method C Appendix C OR Block shear Appendix D OR Dry & wet cleavage Appendix B		Delamination test method A or method B Appendix C OR Dry and wet cleavage Appendix B

NOTE: Where dry and wet cleavage is performed two full cross sections are required.

Figure 13: AS 1328.1 - 1998, Table 2.1

2.6.4 Acceptance criteria for delamination tests

Depending on the method and number of cycles the total delamination percentage of each cross-sectional specimen shall be less than the values given in Table 2.2.

TABLE 2.2

MAXIMUM VALUES FOR THE TOTAL DELAMINATION PERCENTAGES

Method	Applicable to adhesive type	Max. percentage after cycle No:		
		1	2	3
A	Type I	—	5	10
B	Type I	4	8	—
C	Type II	10	—	—

Figure 14: AS 1328.1 - 1998, Section 2.6.4

AS/NZS 1328.1:1998 10

2.6 GLUELINE INTEGRITY

2.6.1 General

The requirements for glueline integrity shall be based on testing of the glueline in a full cross-sectional specimen, which shall be cut from the manufactured glulam member. The specimens shall be representative of the production. The test requirements are summarized in Table 2.1.

2.6.2 Qualification tests

Qualification tests shall be undertaken whenever a new process or process change such as a new adhesive/species combination is introduced.

For members of Service Classes 1 and 2 the testing shall be delamination tests in conformity with method A of Appendix C.

For members of Service Class 3 delamination tests shall be made in conformity with method A of Appendix C.

For each species, adhesive, treatment or process combination, a minimum of 5 full cross-sections shall be tested and shall meet the requirements of 2.6.4 or 2.6.5.

2.6.3 Routine tests

For structures of Service Class 1 the testing shall be either by delamination tests method C of Appendix C, or block shear of Appendix D, or dry cleavage of Appendix B.

For structures of Service Class 2 the testing shall be either by delamination test method C of Appendix C or block shear of Appendix D, or dry and wet cleavage of Appendix B.

For structures of Service Class 3 the testing shall be either by delamination test method A or B of Appendix C, or dry and wet cleavage of Appendix B.

For each shift in which gluing is carried out, one full cross-sectional specimen shall be tested for each press load or every 10 m^3 of production.

Figure 15: AS 1328.1 - 1998, pg. 10

Small samples are needed for the shear test. The samples are tested in a dry condition (20°C, 65% relative humidity) parallel to the grain. These samples are also cut out of production glulam. The test is very similar to that in EN 14080 Annex D.

Requirements exist for finger and face joints. The finger joints must be manufactured according to AS 5068 (see Figure 16). Factory production control (FPC) for finger joints requires that the samples must be tested either with sample testing or proof testing (see Figure 17).

FPC of face joint requires testing defined in Section 4.1.4. (also shown in Figure 17).

2.5 END JOINTS

A1 Finger joints shall be manufactured and tested in accordance with AS 5068. End joints other than finger joints, eg, scarf joints, shall be tested in accordance with the provisions of AS 5068. The alternative end joint shall be treated as a substitute finger joint in interpreting AS 5068. In all such specimens the end joint shall be representative of the normal production method. Where the end joints are cured with the face joints in normal production, the test specimens shall be prepared by an identical method by forming a blank billet. In a blank billet, a glulam member shall be constructed without face joint adhesive so as to provide sufficient (at least 30 for qualification and 3 per shift for routine tests) end joint test specimens. Where such joints are pre-cured they shall be taken directly after the pre-cure operation.

Figure 16: AS 1328.1 - 1998, pg. 10

4.1.3 End joints

End joint quality shall be verified by the testing of sample joints or by proof testing.

4.1.3.1 *Verification by sample testing*

The strength of end joints in laminations shall be verified by testing in flatwise bending in accordance with the provisions of AS 5068. For the purpose of checking finger joint strength to AS 5068, the declared characteristic strength in flatwise bending shall be given by:

$$f'_{\mathrm{b,ej}} = \frac{1.33\, f'_{\mathrm{b}}}{(1 + 0.05\, S_{\mathrm{min}})}$$

2.4.3.1 is an initial qualification test on a gluelam sample, not only on a lamination

NOTE: If f'_{b} has been determined by Method 1 of Clause 2.4.3.1 then it may be advantageous to determine $f'_{\mathrm{b,ej}}$ by flatwise bending tests on end joints in laminations to the AS/NZS 4063 series.

4.1.3.2 *Verification by proof testing*

End joints may be verified by proof testing of laminations in accordance with the following principles:

(a) In beams, the proof testing need only apply to the outer laminations, but for tension members, all laminations shall be proof tested.

(b) The proof load shall apply a stress in bending or tension equal to $f'_{\mathrm{b,pt}}$ or $f'_{\mathrm{t,pt}}$ as applicable. If proof testing takes place before the joints have been fully cured, then the proof testing may be reduced by an amount established by appropriate tests.

4.1.4 Face joints

The face joint gluelines shall be tested in a full cross-sectional specimen, which is to be cut from a cured glulam member produced during each working shift. For each shift in which gluing is carried out, one full cross-sectional specimen shall be taken for every press load or every 10 m^3 of production, whichever is the greater.

If all tests for a 3 month period satisfy the requirements, the number of samples may be reduced to not less than half the number prescribed above, with a minimum of one test per day.

The results of the testing for glueline integrity shall be documented as described in Appendix B, Appendix C and Appendix D for cleavage, delamination and block shear respectively.

Figure 17: AS 1328.1 - 1998, pg. 17

<u>Conclusion:</u>

AS 1328.1 is the current Australian Standard for glulam. This standard:

- Is based on the outdated BS EN 385:1995. EN 14080 is the current European glulam standard.
- Does not include PUR adhesive as it is based on an outdated standard.
- Is not restricted to particular wood species, therefore can be applicable to glulam made from plantation *E. nitens*.
- Specifies the initial qualification test of the completed glulam. It can be done by testing a 300mm deep glulam section.
    - Given the requirements of the European standard (see EN 14080 below), it would be better to test deeper beams. The minimum span length according to the European standard would be 15d (15 x 450mm = 6750mm).
- AS 4364 is the relevant standard for glue manufacture and is described below. Note that this standard covers the glue itself, therefore, it should not be confused with adhesive's performance in the glulam.

Regarding face bonding:

Refer to 'D. Case study of *Eucalyptus nitens*' for the following comments in the context of material testing available at UTAS and industry partners in Biel, Switzerland.

- It is recommended to test block shear and delamination in the first project phase. It has to be discussed which test method shall be used between Australian (AS 1328.1) or European standard (EN 14080).
- Cleavage shall not be tested as it is not relevant for European standards.
- Besides the shear and delamination testing, a further test method needs to be devised.
- Procurement of an autoclave or another device that allows delamination tests (partial vacuum and overpressure) is recommended.

Finger joints:

- Either sample testing or proof testing should be carried out.
- Sample must be tested in bending
- For proof testing, bending or tension tests need to be conducted, according to AS 5068.
- The samples should be manufactured and tested according to AS 5068 described below.

As mentioned earlier, AS 1328.1 is based on an outdated European standard. When hardwood glulam development is undertaken, it must be carefully considered whether to base the testing methods according to the Australian or current European standards.

AS 5068 – 2006 (reconfirmed in 2016): Timber—Finger joints in structural products—Production requirements

Description:

"This standard is a performance-based document that applies to finger jointed hardwood and softwood, used directly with either structural timber or laminations of glue-laminated timber.

This standard requires producers to implement a documented production control system supervised by an inspection body (third party auditor). The production system is established through a research and development program and documented along with all production controls (e.g. wood moisture content, adhesive mix details, etc.). Part of this research and development program involves a mandatory consultation between the producer and adhesive supplier to ensure compatibility of wood species, preservative or fire-retardant treatment method, production processes and the chosen adhesive".

Source: AS 5068-2006, pg. 2, accessed 20th October 2020.

Conditions:

AS 5068 – 2006 Timber – Finger joints in structural products – production requirements, including Amendment 1 – 2010 Production requirements.

Relevant findings:

- No information about CLT found
- For bending and tension tests, the specimen length is not important except for the bending test length that should be greater than 12d
- Both softwood and hardwood are covered, as per Figure 18 below.

This Standard is a performance-based document that applies to finger jointed hardwood and softwood, used directly with either structural timber or laminations of glued laminated timber.

Figure 18: AS 5068 - 2006, pg. 2

The general requirement for finger joint strength is the compliance with an in-factory test which is described in clause 8.2.3 (see Figure 19 below). Initial tests, as referenced in C. Important Tests, are not mentioned.

6.4 Finger joint strength

Finger joints in batches of finger-jointed timber or structural glulam shall be deemed to meet the strength requirements of this Standard provided the provisions of Clause 8.2.3 are met.

Figure 19: AS 5068 - 2006, pg. 8

8.2.3 *Compliance—Finger-jointed timber*

A production batch shall be deemed to comply with the requirements of this Standard when either Items (a) or (b) below are satisfied:

(a) The bending strength ($f_{b,fj}$) or tension strength ($f_{t,fj}$) of each finger joint tested for a sample taken from a production batch satisfies—

(i) $f_{b,fj} \geq 0.74\, f'_{b,timber}$; or

(ii) $f_{t,fj} \geq 0.85\, f'_{t,timber}$.

(b) The mean bending strength ($f_{b,fj,15}$) or the mean tension strength ($f_{t,fj,15}$) of the last 15 finger joints tested from the same production line satisfies—

(i) $f_{b,fj,15} \geq k_{15}\, f'_{b,timber}$; or

(ii) $f_{t,fj,15} \geq k_{15}\, f'_{t,timber}$.

Values of k_{15} are listed in Table 1.

TABLE 1

VALUES OF k_{15}

V*	0.10	0.15	0.20	0.25	0.30	0.35	0.40
k_{15}	0.91	1.00	1.12	1.25	1.39	1.55	1.73

* V is the coefficient of variation established during initial determination of joint strength by testing at least 15 specimens or from historical data recorded in quality control documents.

NOTE: Intermediate values of k_{15} can be estimated by linear interpolation from the following equation:

$k_{15} = 0.735\, e^{2.09V}$

Figure 20: AS 5068 - 2006, pg. 11

Regarding the adhesive for Service class 2, a wet test with vacuum and overpressure has to be conducted. Therefore, an autoclave would be required to perform this test (refer to Figure 21 below). See 'D. Case study of *Eucalyptus nitens*' for how this test may fit into the development of hardwood glulam.

11 AS 5068—2006

8.3 Assessment of adhesive bond durability for Service Class 2 or 3 exposure

8.3.1 *Sampling*

A sample of at least four joints per month shall be taken from the production for testing; specimens shall be drawn at a rate of one specimen per week.

8.3.2 *Wet conditioning of specimens*

Specimens shall be conditioned as follows:

(a) Place the finger joints in an autoclave, immerse them in water between 10°C and 27°C and weigh them down.

(b) Draw a vacuum of at least 65 kPa or at least 500 mm Hg and hold it for 1.5 h, then release the vacuum and apply a pressure of 500 ±30 kPa for 1.5 h. Repeat this vacuum-pressure cycle once more.

NOTE: For higher density species, longer pressure and vacuum cycles may be required to achieve acceptable penetration.

8.3.3 *Testing*

The specimens shall be tested in bending according to Appendix B or tension according to Appendix C and the fracture surfaces shall be examined for wood failure.

8.3.4 *Compliance*

The bond shall be deemed to meet the requirements of this Standard provided the wood failure percentages given in Table 2 are met.

TABLE 2

WOOD FAILURE

percent

	Average	Minimum
Hardwood	40	20
Softwood	60	30

NOTE: The values are to be interpreted as the average for all fingers.

Figure 21: AS 5068 - 2006, pg. 11

The application of PUR for finger joints is permitted, as mentioned in the standard (except for Service Class 3) shown in Figure 22 below.

TABLE A1

TYPE OF ADHESIVE FOR GIVEN SERVICE CONDITIONS

Description	Service Class(1)		
	1	2	3
	Interior dry	Interior—Humid, exterior protected	Interior—Hot and humid, exterior exposed
Timber EMC	≤12%	≤18%	>18% untreated timber >20% multi-salts treated softwood
Adhesive(2)	Type I or Type II	Type I or Type II, provided the temperature remains below 50°C	Type I
Adhesive examples(3)	— Aqueous polymeric isocyanates/Emulsion polymeric isocyanates — Melamine-urea formaldehyde — Phenol-resorcinol formaldehyde — Polyurethanes — Resorcinol formaldehyde — Tannin formaldehyde	— Aqueous polymeric isocyanates/Emulsion polymeric isocyanates — Melamine-urea formaldehyde — Phenol-resorcinol formaldehyde — Polyurethanes — Resorcinol formaldehyde — Tannin formaldehyde	— Phenol-resorcinol formaldehyde — Resorcinol formaldehyde — Tannin formaldehyde Important: PU(R) mentioned here --> PU(R) for finger jointing therefore ok (except for Service Class 3).

Figure 22: AS 5068 - 2006, pg. 12

<u>Conclusion:</u>

Findings from AS 5068 – 2006 are:

- A batch of finger jointed timber product is deemed to comply with this standard if bending or tension tests are undertaken, as per Figure 20 above.
- A wet test is required. The recommended equipment is an autoclave or another device that allows conducting partial vacuum and overpressure test if necessary.
- PUR can be used for the finger joints, for Service Class 1 and 2.

AS/NZS 4364: 2010: Timber—Bond performance of structural adhesives

<u>Description:</u>

"AS 4364 – 2010 – Timber – Bond performance of structural adhesives specifies the performance requirements for adhesives according to their suitability for use in prefabricated timber components for structural use in defined environmental conditions and for such adhesives for the manufacture of structural finger-jointed timber and glulam".

Source: AS 4364, pg. 5, accessed: 21st October 2020.

<u>Relevant findings:</u>

This standard is chiefly for glue producers (see AS/NZS 4364:2010, page 5).

Australian/New Zealand Standard

Timber—Bond performance of structural adhesives

2 APPLICATION

This Australian/New Zealand Standard is intended to be used primarily by adhesive manufacturers.

Figure 23: AS 4364 - 2010, pg. 5

The following requirements and tests are mentioned:

Figure 24: AS 4364 - 2010, pg. 3

Shear, delamination and creep tests:

There are two test methods listed, Test Methods A and B. Method A is based on a Canadian standard. Method B is identical to the referred European standards EN 302-1 (shear), EN 302-2 (delamination test, described below) and 15416 – 2 (creep resistance). The following example in Figure 25 shows illustratively that these requirements can be fulfilled with the respective European tests.

Important notes:

- For these three tests, the specimens must be produced specifically for the test. This requirement is in contrast to the test specimens for shearing and delamination in AS 1328.1, which are cut from glulam.
- A creep test is not described in AS 1328.1, in contrast to EN 14080 (Annex B.2).
- The wood species to be tested is maple if the glulam shall be produced of hardwood.
- It may be more suitable to use plantation *E. nitens* for the test in this project, but this has to be further discussed.

9 AS/NZS 4364:2010

6.6.3 *Method B—Tensile shear*

When tested in accordance with EN 302-1, the tensile shear test result shall meet the requirements specified in EN 301.

6.7 Delamination resistance

6.7.1 *General*

Delamination tests shall be carried out in accordance with Method A, as specified in Clause 7.6.1, or Method B, as specified in Clause 7.6.2, and shall meet the requirements specified in Clause 6.7.2 or 6.7.3, as appropriate.

6.7.2 *Method A*

6.7.2.1 *Evaluation for hardwoods*

When tested in accordance with Clause 7.6, the total delamination within any one bondline shall not exceed 1.6% of the total length of the bondline in the assembly.

6.7.2.2 *Evaluation for softwoods*

When tested in accordance with Clause 7.6, the total delamination within any one bondline shall not exceed 1% of the total length of the bondline in the assembly.

6.7.3 *Method B*

When tested in accordance with EN 302-1, the delamination result shall meet the requirements specified in EN 301.

prob. mistake, should be 302-2, see 7.6.2

Figure 25: AS 4364:2010, pg. 9

7 SAMPLE PREPARATION AND TEST METHODS

7.1 Anti-fungal properties

Testing for anti-fungal properties shall be in accordance with ASTM D4300.

7.2 pH of cured adhesive film

Testing for pH of cured adhesive film shall be in accordance with ASTM D1583.

7.3 Wood species and density

7.3.1 *Hardwood*

When adhesives for hardwoods are tested in accordance with Clauses 7.5 to 7.7, the tests shall be performed on hard maple (*acer saccharum* or *acer nigrum*) of density specified in Clause 7.3.3, or the species specified in the relevant EN Standard.

Figure 26: AS 4364:2010, pg. 10

<u>Conclusion:</u>

Shear strength, delamination resistance and creep resistance can be tested in accordance with European standards rather than AS 4364, as they are identical (the Canadian-standard-based tests do not have to be considered). These tests could be omitted, as long as the shear and delamination tests in AS 1328.1 (or the ones in EN 14080) were conducted. A glue producer should be involved in this level of testing.

EN 14080: 2013: Timber structures - Glued laminated timber and glued solid timber - Requirements

Description:

"Performance requirements of the following glued laminated products: glued laminated timber (glulam), glued solid timber, glued with large finger joints, and block glued glulam for use in buildings and bridges".

Source: www.infostore.saiglobal.com/en-us/Standards/EN-14080-2013, accessed: 20th October 2020.

Conditions:

The official standard EN 14080: 2013 was only available in German. Screenshots have been taken from the final draft in English.

Relevant findings:

EN 14080 is the European standard for glulam.

This standard covers many softwood species and poplar but no other hardwoods. Development of the standard for hardwood glulam is in progress, see WI 124xxx:2018 below. Under certain circumstances, other hardwoods can be used (refer to Figure 27 below):

1 Scope

This European Standard sets the performance requirements of the following glued laminated products:

— Glued laminated timber (glulam);

— Glued solid timber;

— Glulam with large finger joints;

— Block glued glulam

for use in buildings and bridges.

It also lays down minimum production requirements, provisions for evaluation and attestation of conformity and marking of glued laminated products.

This European Standard is applicable for glued laminated timber made of coniferous species listed in this standard or poplar consisting of two or more laminations having a thickness from 6 mm up to 45 mm (inclusive).

It may be possible to produce glulam made from specific hardwood species based on some provisions of this European standard. In this case Annex ZA does not apply.

Figure 27: EN 14080:2013, pg. 8

Two testing types should be distinguished:

- Initial type testing (all tests listed in section 6.2, Table 15, Figure 28 below). Initial tests include MOR, MOE and further tests
- Factory production control (FPC), in other standards also referred to as Daily quality control test or Routine test (all tests listed in section 6.3, table 16)

Table 15 *(continued)*

Characteristics	Requirement clause	Test-/Assessment method	Test sample	Acceptance criteria
Mechanical resistance of glued laminated timber expressed as modulus of elasticity, bending strength, compressive strength, tensile strength and shear strength				
Bending strength, compressive strength, tensile strength, shear strength, modulus of elasticity, density of glued laminated timber	5.1.6.3	or 5.1.6.3 (test)	Only for glulam for which mechanical resistance is derived from full scale tests: 30 glulam specimens	5.1.6.3
Additionally for resawn glulam	5.1.7	5.1.7 (check)	-	5.1.7
Geometrical data	5.11	5.11 (check)	General	5.11

Figure 28: EN 14080:2013

For the Initial test, MOR and MOE can be verified from full-scale tests with glued laminated timber.

It is recommended to perform the test with full-scale glulam to gain knowledge and about the static behaviour under bending. The full-scale test will provide more specific information than the classifications, according to 5.14 and 5.15. The test should be done in accordance with EN 408.

The standard depth of the glulam is 600mm, in contrast to AS 1328.1 by which the depth is only 300mm. Refer to Figure 29 below.

5.1.3 Related material properties

The characteristic strength, stiffness and density properties of glued laminated timber shall be verified either:

— from classifications from layups and lamination properties according to 5.1.4, or

— from cross sectional layups and documented properties of boards and finger joints according to 5.1.5 or

— from full scale tests according to 5.1.6.

The characteristic strength, stiffness and density properties may be declared by reference to a strength class according to Table 3 or 4 or to a manufacturer's specific strength class. If a manufacturer's specific class name starting with GLxx is chosen (where "xx" is the characteristic bending strength) it shall be accompanied by the Company name, e.g GL 30 Any Company. For glulam having an asymmetrical layup, "ca" has to be added to the class name, e.g. GL28 ca. The class name of resawn glulam shall be marked by "s", e.g. GL24 cs. For brick bonded glulam according to I.5.2, the denomination of strength class shall be accompanied by "brick-bonded".

The characteristic bending strength shall be valid for glulam with a depth h of 600 mm and a lamination thickness of t = 40 mm. If the lamination thickness is less than 40 mm, the bending strength may be multiplied by k as given in Formula (1). For lamination thicknesses 40 mm < $t \le$ 45 mm it is not necessary to take any strength modification into account.

$$k = \min \begin{cases} \left(\frac{40}{t}\right)^{0,1} \\ 1{,}05 \end{cases} \qquad (1)$$

where

t is the lamination thickness in mm.

The characteristic tensile strength parallel to the grain shall be valid for glulam with depth h of 600 mm or width b of 600 mm.

The characteristic tensile strength perpendicular to the grain shall be valid for glulam with a stressed volume of 0,01 m^3.

The 5%-fractile of a shear modulus or a modulus of elasticity shall be estimated from the mean value by applying the ratio of $G_{g,k}/G_{g,mean}$ = 5/6 and $E_{0,g,k}/E_{0,g,mean}$ = 5/6, respectively.

For glued laminated timber members made of at least ten laminations the product ($E_{0,g,k}$ $G_{g,k}$) may be increased by a factor k = 1,40.

Figure 29: EN 14080:2013, pg. 18

For homogeneous glulam (see 5.1.6.3.2), only MOR and MOE have to be verified through full-scale tests, whereas for combined glulam (see 5.1.6.3.1), further tests are necessary such as the characteristic compression strength. The tests other than MOR and MOE test are not discussed in this document as they are not the focus of this review.

The density of a combined glulam shall be taken as the weighted densities of the lamination zones estimated as the densities of homogeneous glulam according to Table 6.

5.1.6 Verifications from full scale tests with glued laminated timber

5.1.6.1 Properties of the boards

The characteristic values of the tensile strength parallel to the grain $f_{t,0,l,dc,k}$ or the bending strength $f_{m,l,dc,k}$, the mean modulus of elasticity parallel to the grain $E_{t,0,l,dc,mean}$ and the characteristic density $\rho_{l,dc,k}$ of the boards shall be estimated and declared by tests according to Annex E.

5.1.6.2 Strength of finger joints

The characteristic flatwise bending strength of the finger joints $f_{m,j,dc,k}$ shall be estimated and declared by tests according to Annex E.

The declared characteristic flatwise bending strength of the finger joints $f_{m,j,dc,k}$ shall be not less than 1,4 $f_{t,0,l,dc,k}$.

5.1.6.3 Strength, stiffness and density properties of glued laminated timber derived from testing

5.1.6.3.1 Combined glued laminated timber

Combined glued laminated timber shall be assigned to one of the strength classes given in Table 4 or to any other manufacturer specific strength class if the characteristic bending strength parallel to the grain $f_{m,g,k}$, the mean modulus of elasticity parallel to the grain $E_{0,g,mean}$ and the characteristic density derived from full scale tests according to Annex F and the characteristic tensile strength $f_{t,0,g,k}$ and the compression strength $f_{c,0,g,k}$ parallel to the grain tested according to EN 408 and derived according to EN 14358 are not less than the declared values. Characteristic tensile strength $f_{t,0,g,k}$ and compression strength $f_{c,0,g,k}$ parallel to the grain may be taken as the values for the lamination zone having the lowest characteristic tensile strength parallel to the grain $f_{t,0,l,k}$.

The other strength and stiffness properties of a manufacturer specific strength class shall be calculated using the expressions given in Table 6.

5.1.6.3.2 Homogeneous glued laminated timber

Homogenous glued laminated timber shall be assigned to one of the strength classes given in Table 5 or to any other manufacturer specific strength class if the characteristic bending strength parallel to the grain $f_{m,g,k}$, the mean modulus of elasticity parallel to the grain $E_{0,g,mean}$ and the characteristic density $\rho_{g,k}$ derived from full scale tests according to Annex F are not less than the declared values.

The other strength and stiffness properties of a manufacturer specific strength class shall be calculated using the formulae given in Table 6.

Figure 30: EN 14080:2013

Initial tests – Gluing:

Relevant passages regarding glue from Table 15. The highlighted texts are discussed below in Figure 31.

Bonding strength expressed as				
Strength of finger joints in laminations for glued laminated timber	5.1.4.2 or 5.1.5.2 or 5.1.6.2	As for mechanical resistance of glued laminated timber		
Strength of finger joints in laminations for glued solid timber	5.5.4.2 or 5.2.5.2.	As for mechanical resistance of glued solid timber		
Glue line integrity of laminations in glued laminated timber or glued solid timber	5.5.5.2.2	According to Annex C (test)	for each combination of species and adhesive 10 full cross sectional specimens	5.5.5.2.2
Bending strength of large finger joints	5.3	As for mechanical resistance of glulam with large finger joints		
Bonding strength of glue lines of block glued glulam	5.5.7.2	Annex C (test) or Annex D (test)	2 specimens	5.5.5.2.2 5.5.5.2.3
Durability of bonding strength as				
Species	5.5.2	5.5.2 (check)	-	5.5.2
Moisture of timber to be bonded[b]	G.1	G.1 (test)	100 timber pieces for each species	G.1

Figure 31: EN 14080:2013, pg. 44

FprEN 14080:2013 (E)

Table 15 *(continued)*

Characteristics	Requirement clause	Test-/Assessment method	Test sample	Acceptance criteria
Durability of bonding strength as				
Adhesive characteristics	5.5.3.1 and 5.5.3.2.1 General requirements for phenolic and aminoplastic adhesives[b]	prEN 302-1, -2, -3, -4 and -6 (test)	acc. to prEN 302-1, -2, -3, -4 and -6	The requirements for the respective adhesive type class and subclass given in prEN 301 shall be fulfilled and the conventional pressing time according to prEN 302-6 shall be declared.
	5.5.3.2.2 Additional requirements for phenolic and aminoplastic adhesives for separate application of resin and hardener for the production of finger joints in laminations	prEN 302-1, -2, -3 and B.3[b]	5.5.3.2.2	5.5.3.2.2
		and B.3	5.5.3.2.2	5.5.3.2.2
		and Annex E	5.5.3.2.2	5.1 or 5.2
	5.5.3.2.3 Additional requirements for gap filling adhesives[b]	prEN 302-6	prEN 302-6	prEN 302-6
	5.5.3.1 and 5.5.3.3 Moisture curing one-component polyurethane adhesives[b]	EN 15425 (test)	EN 15425	EN 15425
		and B.2 (test)	80	B.2
		and prEN 302-2:2011, 5.1, 2nd para. (test) or	prEN 302-2:2011, 5.1, 2nd para.	prEN 302-2:2011, 5.1, 2nd para.
		For adhesives only to be used for finger joints in larch laminations: B.3	Analogue to 5.5.3.2.2, 1st dash	B.3
		and EN 15416-5 (test)	EN 15416-5	The conventional pressing time acc. to EN 15416-5 shall be declared
	5.5.3.1 and 5.5.3.4 Emulsion polymer isocyanate adhesives[b]	EN 15425 (test)	EN 15425	5.5.3.4
		and B.2 (test)	80	B.2
		and prEN 302-6 (test)	prEN 302-6	The conventional pressing time according to prEN 302-6 shall be declared

Figure 32: EN 14080:2013, pg. 44

Finger joints:

Refer to Figure 31 above: 5.1.4.2, 5.1.5.2 or 5.1.6. are to be tested under standard climate on bending strength or in some cases on tension strength instead of bending strength according to Annex E, which refers to the test methods in EN 408. The number of samples is also given in the table.

It is noted that according to EN 408, the specimen's length for tension tests has to be 9 times the with or thickness of the specimen.

These samples can be cut from the produced finger jointed laminations and do not have to be produced specifically for this test.

Finger joints in laminations	5.1.4.2 or 5.1.5.2	Annex E (test)	General, for each combination of species, adhesive and declared strength value: – For laminations complying with Table 1: 15 finger joints in laminations – For laminations not complying with Table 1: 100 finger joints in laminations from at least three batches	5.1.4.2 or 5.1.5.2
	5.1.6.2		For glulam for which mechanical resistance has been derived from full scale tests, for each combination of species, adhesive and cross-sectional layup: – For laminations complying with Table 1 : 30 finger joints in laminations – For laminations not complying with Table 1: 100 finger joints in laminations from at least three batches	5.1.6.2

Figure 33: EN 14080:2013, pg. 42

Glue line integrity:

The test procedure is specified in Annex C of this standard, which describes three different delamination test methods A, B and C. They are all similar (applying a partial vacuum and after overpressure and drying of the wood in varied conditions).

These tests are also very similar to the three delamination methods in AS 1328.1 Appendix C. They differ regarding time, pressure, drying conditions, and the number of cycles. The sample size is always the same (see figure C1), and the samples are cut out of the glulam produced. No separate sample is required, but gluing is needed specifically for the test.

If the cross-section is large, smaller samples can be used (see the marked passage in the screenshot). It is more practical because the test equipment can be smaller.

C.3 Sampling and preparation of test pieces

The test pieces shall be prepared or selected in such a manner that they are representative of the production run.

Each test piece shall be taken from a full cross section of the specimens to be tested, prepared by cutting perpendicular to the grain of the wood. It shall be (75 ± 5) mm in length (along the grain).

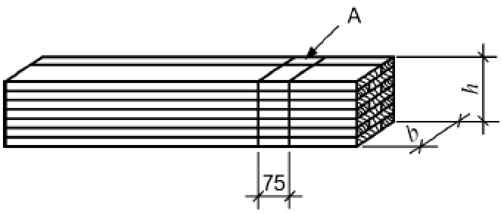
63

FprEN 14080:2013 (E)

The end grain surfaces of the test piece shall be cut with a sharp saw or tool that produces a smooth surface.

If the width *b* of the cross section is greater than 300 mm the test piece may be lenghtwise cut into two or more test pieces each at least 130 mm wide. If the depth *h* is greater than 600 mm the test piece(s) may be cut into two or more pieces each with a depth of at least 300 mm (see Figure C.1).

Dimensions in mm



Key

A test piece

b width

h depth

Figure C.1 — Test piece cut from glued laminated timber having a width *b* of more than 300 mm

Figure 34: EN 14080:2013, pg. 63

5.5.5.2.2 Glue line integrity

Where the glue line integrity is tested by the delamination test method A, B or C, given in Annex C, the total delamination percentage of each cross sectional specimen shall meet the requirements given in Table 9.

Table 9 — Maximum values for the total delamination in %

Type [a]	Number of cycles	1	2	3
Glued laminated timber, Glulam with large finger joints and block glued glulam	Method A	–	5	10
	Method B	4	8	–
	Method C	10	–	–
Glued solid timber with lamination thicknesses from 60 mm up to 85 mm (inclusive)	Method A	–	10	15
	Method B	8	12	–
	Method C	15	–	–

[a] For Glued solid timber having lamination thicknesses from 45 mm up to 60 mm linear interpolation applies.

For all delamination methods the maximum delamination percentage of a single glue line shall be less than or equal 30 %.

Figure 35: EN 14080:2013

The maximum delamination values are defined in table 9 of this standard, Figure 35 above.

The durability of bonding strength:

Adhesive characteristics are presented in Table 15, Figure 31, Figure 32 and Figure 33.

Principally three different adhesive types can be used (see also a), b) and c) in the following screenshot, (Figure 36) and they have different requirements.

It is noted that PUR cannot be used according to this standard for large finger joints and for glue lines between glulam components of block glued glulam (see table 7, Figure 36).

It is also important to mention that, if preservative treatments are done before the bonding, it shall be documented that the requirements are fulfilled for the combination of the preservative and adhesive.

FprEN 14080:2013 (E)

5.5.3 Adhesives for the production of glued laminated products

5.5.3.1 General

Adhesives shall provide durable bonds in glued laminated products throughout the lifetime of the structure for the required service class according to EN 1995-1-1. For glued laminated products used in service class 1 adhesives, which can be assigned to an adhesive type I or II according to prEN 301:2011, Table 1, or EN 15425:2008, Table 1, shall be used. For glued laminated products used in service class 2 or 3 adhesives, which can be assigned to an adhesive type I according to prEN 301:2011, Table 1, or EN 15425:2008, Table 1, shall be used.

The applicability of adhesives in different service classes may be further limited by national provisions valid at the place of use.

Emulsion polymer isocyanate adhesives shall also be assigned to an adhesive type according to EN 15425:2008, Table 1.

Taking into account the restrictions given in the referred subclauses, the following adhesive families are applicable:

a) phenolic and aminoplastic adhesives (e.g. MF, MUF, PRF, UF) in accordance with 5.5.3.2;

b) moisture curing one-component polyurethane adhesives (PUR) in accordance with 5.5.3.3;

c) emulsion polymer isocyanate adhesives (EPI) in accordance with 5.5.3.4.

If a preservative treatment is done before the bonding of the laminations it shall be documented that the requirements are fulfilled for the combination of the preservative and adhesive.

The applicability of an adhesive for a glued laminated product or its components covered by this European Standard shall be taken from Table 7.

Table 7 — Applicability of adhesives for components and products

	Relevant requirements for the application of		
	Phenolic and aminoplastic adhesives	**Moisture curing one-component polyurethane adhesives**	**Emulsion polymer isocyanate adhesives**
Finger joints in laminations for glulam and glued solid timber	5.5.3.2.1 and 5.5.3.2.2 (if relevant)	5.5.3.3	5.5.3.4
Glue lines between laminations for glulam and glued solid timber	5.5.3.2.1	5.5.3.3	5.5.3.4
Large finger joints	5.5.3.2.1 mixed before used	Not applicable	Not applicable
Glue lines between glulam components of block glued glulam	5.5.3.2.3	Not applicable	Not applicable

Figure 36: EN 14080:2013

Phenolic and aminoplastic adhesives fulfil the requirements in EN 301 and are to be tested according to ‘EN 302-6, Adhesives for load-bearing timber structures — Test methods — Part 6: Determination of the minimum pressing time under referenced conditions’ (see Figure 37).

EN 301 is equivalent to EN 15425 for phenolic and aminoplastic adhesives other than PUR and refers to many test standards such as EN 302-1 and 302-2. Figure 38 shows the many tests required (note, this is a screenshot from an outdated version).

5.5.3.2 Phenolic and aminoplastic adhesives

5.5.3.2.1 General requirements

Phenolic and aminoplastic adhesives shall fulfil the requirements of prEN 301 and shall be tested according to prEN 302-6.

Figure 37: EN 14080:2013, pg. 31

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

EN 302-1, *Adhesives for load-bearing timber structures - Test methods - Part 1: Determination of longitudinal tensile shear strength*

EN 302-2, *Adhesives for load-bearing timber structures - Test methods - Part 2: Determination of resistance to delamination*

EN 302-3, *Adhesives for load-bearing timber structures - Test methods - Part 3: Determination of the effect of acid damage to wood fibres by temperature and humidity cycling on the transverse tensile strength*

EN 302-4, *Adhesives for load-bearing timber structures - Test methods - Part 4: Determination of the effects of wood shrinkage on the shear strength*

EN 408, *Timber structures - Structural timber and glued laminated timber - Determination of some physical and mechanical properties*

EN 923, *Adhesives - Terms and definitions*

EN 1245, *Adhesives - Determination of pH*

EN 1995-1-1, *Eurocode 5: Design of timber structures - Part 1-1: General - Common rules and rules for buildings*

EN 12092, *Adhesives - Determination of viscosity*

EN 13183-2, *Moisture content of a piece of sawn timber - Part 2: Estimation by electrical resistance method*

Figure 38: EN 14080:2013, pg. 5

PUR Adhesives:

In Annex B.2 of EN 14080, PUR adhesives are discussed, with regard to minimal conventional pressing time of a glue line.

EN 15425 is the standard *'Adhesives for load-bearing timber structures other than phenolic and aminoplastic — Test methods — Part 5: Determination of conventional pressing time*'. EN 15425 refers to many detailed tests. One test mentioned is EN 302-2, which is explained below (see Figure 39).

EN 15416-5 should be considered for PUR if the glue producer cannot recommend a minimal pressing time for the glue used at envisaged pressing pressure, temperature and wood moisture content. This could be tested with a simple self-developed test or according to EN 302-6 or EN 15416-5 respectively if it should be tested in line with the standards.

In Annex B.2, a long-term test is conducted over up to 12 months at cyclic climate conditions.

It is noted that for the initial tests, most of the samples should be made specifically for the test and should not be simply cut from the glulam (in contrast to the tests for the Factory production control, Figure 40 below). The description of the examples is provided in EN 302-2.

For consideration is the long-term test (creep test) according to Annex B.2, if PUR (or EPI) is used. It has to be determined whether this test is required or not.

5.5.3.2.3 Additional requirements for gap filling adhesives

The minimum conventional pressing time of a glue line having a thickness of 1 mm shall be determined as specified in prEN 302-6.

5.5.3.3 Moisture curing one-component polyurethane adhesives

Moisture curing one-component polyurethane adhesives shall fulfil the requirements of EN 15425 and B.2 taking into account the conditions given in B.1.

The requirements given in prEN 302-5:2011, 5.1, 2nd paragraph apply. For moisture curing one-component polyurethane adhesives to be used in finger joints in larch wood the delamination test according to prEN 302-2 may be replaced by tests according to Annex B.3 with larch wood.

The influence of the climate on the conventional pressing time shall be verified in accordance with EN 15416-5.

5.5.3.4 Emulsion polymer isocyanate adhesives

5.5.3.4.1 General

Emulsion polymer isocyanate adhesives shall only be used for glued laminated products to be used in service classes 1 and 2.

Emulsion polymer isocyanate adhesives shall be tested in accordance with EN 15425 and B.2 taking into account the conditions given in B.1 and the respective requirements shall be fulfilled.

Figure 39: EN 14080:2013, pg. 32

Factory production control (FPC) – MOR, MOE and further tests:

The tests listed do not exceed the requirements of the initial tests in Figure 40 below. All these tests can be done with samples from the glulam production process and do not have to be made specifically for the tests.

Note that the test frequency is given in table 16 (Figure 40), refer to C. Important Tests for context.

Table 16 — Factory production control for glued laminated products

Property	Clause, indicating the relevant test or evaluation method	Acceptance criteria	Minimum frequency
Mechanical resistance of glued laminated products			
Strength, stiffness and density properties of timber	5.1.2	General, for timber graded by the manufacturer of the glued laminated products: EN 14081-1:2011, 6.3 General, for timber not graded by the manufacturer of the glued laminated products: -	According to EN 14081-1:2011, 6.3 Check suppliers declaration according to EN 14081-1:2011, Clause 7, on receipt
	E.5	Additionally for glulam for which mechanical resistance has been derived from full-scale tests: $f_{m,k,l}$ determined according to E.5 shall be greater than or equal to $f_{m,k,l,dc}$ (determined within ITT)	2 boards per shift and line, layup, strength class or manufacturer specific strength class
Finger joints in laminations	Annex E	see E.3 and declared values according to 5.1.4.2 or 5.1.5.2 or 5.1.6.2 (glulam) or 5.2.4.2 or 5.2.5.2 (glued solid timber)	at least 3 per shift and line, highest strength class or manufacturer specific strength class and adhesive

Figure 40: EN 14080:2013, pg. 49

Factory production control (FPC) – Gluing:

Regarding FPC – Gluing, the majority of tests listed do not exceed the requirements of the initial tests. One exception is the shear test in Annex D, which can be tested in place of the delamination test (Annex C), refer to Figure 41 below. This is not a common occurrence, as both shear and delamination tests provide important information about the glue line. It is common to perform both delamination and shear tests. The test frequency is also listed.

All tests noted can be done with samples from the glulam production process and do not have to be made specifically for the tests.

Bonding strength			
Finger joints in laminations	5.1.4.2 or 5.1.5.2 or 5.1.6.2 (glulam) or 5.2.4.2 or 5.2.5.2 (glued solid timber)	As for mechanical resistance	
Bonding strength of glue lines in glued laminated timber or glued solid timber	Annex C	see 5.5.5.2.2	for each shift in which gluing is carried out one full cross sectional specimen for each 20 m^3 of production or part thereof.[a]
	or Annex D	see 5.5.5.2.3	
	I.5.8	I.5.8	
Large finger joints	I.6.6	I.6.6	at each change of dimension, at least one per shift
Bonding strength of block glued glulam	method B as given in Annex C	see 5.5.5.2.2	for each shift in which gluing is carried out, each species and adhesive at least two drill cores having a geometry as given in Figure D.7 or one end-cut[b]
	or Annex D	see 5.5.5.2.3	
	I.7.4	I.7.4	

Figure 41: EN 14080:2013, pg. 50

Table 16 *(continued)*

Property	Clause, indicating the relevant test or evaluation method	Acceptance criteria	Minimum frequency
Durability of bonding strength			
Species	5.5.2	5.5.2	Check the suppliers declaration at each reception
Adhesive	5.5.3	-	Adhesives for the production of finger joints or glue lines between laminations: Check the suppliers declaration at each reception Adhesives for large finger joints or glue lines between components of block glued glulam: At each shift in which products are produced
Moisture content of timber to be jointed	G.1	G.1	Measurement according to the quality manual of the manufacturer of the glued laminated product
	and G.2 (if relevant)	G.2	At least one measurement per month
Durability of other characteristics against biological attack			

Figure 42: EN 14080:2013, pg. 50

Shear test in Annex D:

The test method of the shear test is provided in Annex D:

- Small specimens are cut from the glulam produced with no separate making and gluing of samples
- Testing of the glue line parallel to the grain should be carried out in dry conditions (20°C, 65% relative humidity)
- This method is almost the same as the one in AS 1328.1
- The minimum wood failure percentages are given in Table 10, Figure 44 (note: it is the same table as in AS 1328.1)

5.5.5.2.3 Shear strength of glue lines

Where the shear strength of the glue lines is tested according to Annex D, each test result shall comply with the following requirements with regard to the shear strength and the wood failure percentage.

The shear strength of each glue line shall be at least 6 N/mm², see Table 10, individual values. A shear strength of 4 N/mm² shall be regarded as acceptable if the wood failure percentage is 100, see Table 10, individual values.

The average wood failure percentage of a cross sectional specimen and any individual values shall exceed the minimum wood failure percentages stated in Table 10.

Figure 43: EN 14080:2013, pg. 34

Table 10 — **Minimum wood failure percentages relating to the shear strength f_v** [a]

	Average			Individual values		
Shear strength f_v, in N/mm²	6	8	$f_v \geq 11$	$4 \leq f_v < 6$	6	$f_v \geq 10$
Minimum wood failure percentage, in % [b]	90	72	45	100	74	20

[a] For values in between linear interpolation shall be used.

[b] For average values the minimum wood failure percentage shall be: 144 – (9 f_v). For the individual values the minimum wood failure percentage for the shear strength $f_v \geq 6,0$ N/mm² shall be: 153,3 – (13,3 f_v).

Figure 44: EN 14080:2013, pg. 34

Conclusion:

The standard EN 14080 does not cover hardwood apart from poplar.

Compared to AS 1328.1, there are several differences and considerably more tests in EN 14080. For example:

- Many of the tests in EN 301 (for phenolic and aminoplastic adhesives) and EN 15425 (for PUR adhesives) are not mentioned or described in AS 1328.1
- PUR is well covered in EN 14080
- For full-scale tests, the standard depth of the glulam beam is 600mm in EN 14080 and 300mm in AS 1328.1

As described above the EN 14080 standard has a greater breadth of tests listed, and where the requirements for EN 14080 supersede AS 1328.1, glulam producers in Australia would utilise the European standard to develop a new material (refer to D. Case study).

WI 124xxx:2018 (IN PROGRESS): Timber structures — Hardwood glued laminated timber — Requirements

Description:

'This European Standard sets out requirements regarding the performance of characteristics of the following types of glued laminated products made of hardwood to be used in buildings and bridges. Type 1: hardwood glued laminated timber (hardwood glulam). Type 2: hardwood block glued glulam'.

Source: WI 124xxx:2018, accessed: 27th October 2020.

Conditions:

This European standard for hardwood glulam timber is currently still in development. The final version is expected to be published in 2021. This new standard will provide hardwood specific requirements and tests. This report has reviewed the draft of WI 124xxx 2018, and many elements in this new standard are similar to EN 14080.

Relevant findings:

No restrictions regarding hardwood species or plantation timber were found.

Regarding glue and bonding, this standard is similar to EN 14080. Some key points include:

- Shear strength and delamination resistance are mentioned.
- Creep resistance is not mentioned.
- For shear strength, a wet shear test is envisaged, but no description about it is found so far (see WD W1 124xxx:2019 (E) on page 20).
- Delamination test similar or identical to the ones in EN 14080
- Only adhesive type I is allowed and the use of PUR is generally accepted.

Many of the standards referred in this standard (see WD W1 124xxx:2019 (E), page 6 and 7) are the same as the ones referred to in EN 14080.

WD WI 124xxx:2019 (E)

1 Scope

This European Standard sets out requirements regarding the performance of characteristics of the following types of glued laminated products made of hardwood (hardwood glued laminated products) to be used in buildings and bridges:

— Type 1: hardwood glued laminated timber (hardwood glulam);

— Type 2: hardwood block glued glulam.

NOTE Glued laminated timber made of specific softwoods and poplar is covered in EN 14080.

It also lays down procedures for assessment and verification of constancy of performance (AVPC) of characteristics and specifies marking and labelling.

This European Standard covers hardwood glued laminated products:

— manufactured according to this standard, which sets up provisions for:

  — boundary conditions during manufacture;

  — moisture content and temperature of timber to be bonded;

  — combinations of species and adhesives;

  — lamination and overall sizes;

  — production of finger joints and bonds between layers;

  — production of glue lines between hardwood glulam components (for Type 2 only).

— bonded with phenolic or aminoplastic or moisture curing one-component polyurethane or emulsion polymer isocyanate adhesives of adhesive type I according to the respective adhesive standard;

Figure 45: WI 124xxx:2018

Conclusion:

Until the estimated publication of the final version in 2021, the review will not be complete. However, it's important to observe updated draft versions and final version and consider new tests or adapt the ones from AS 1328.1 or EN 14080

Since this will be the first standard for glulam made of hardwood, it refers to many other standards also referred to in EN 14080. For this reason, it consequently seems reasonable to adopt EN 14080 and WI 124 over AS 1328.1.

EN 408:2010-12: Timber structures – Structural timber and glued laminated timber – Determination of some physical and mechanical properties

Description:

'This European Standard specifies test methods for determining the following properties of structural timber and glued laminated timber: modulus of elasticity in bending; shear modulus; bending strength, modulus of elasticity in tension and tension strength parallel to the grain; modulus of elasticity in compression and compression strength parallel to the grain; modulus of elasticity in tension and tension strength perpendicular to the grain; modulus of elasticity in compression and compression strength perpendicular to the grain; and shear strength'.

Source: EN 408:2010-12, accessed: 27th October 2020.

Relevant findings:

With regard to the test arrangement for measuring bending strength, in contrast to AS 1328.1, EN 408 allows the span to be reduced from 18h to 15h with a tolerance of 1.5h on each side of the beam, refer to Figure 46 below. The distance between the two upper loading heads, however, has to be 6h (as per AS 4063.1) and cannot be reduced.

DIN EN 408:2012-10
EN 408:2010+A1:2012 (E)

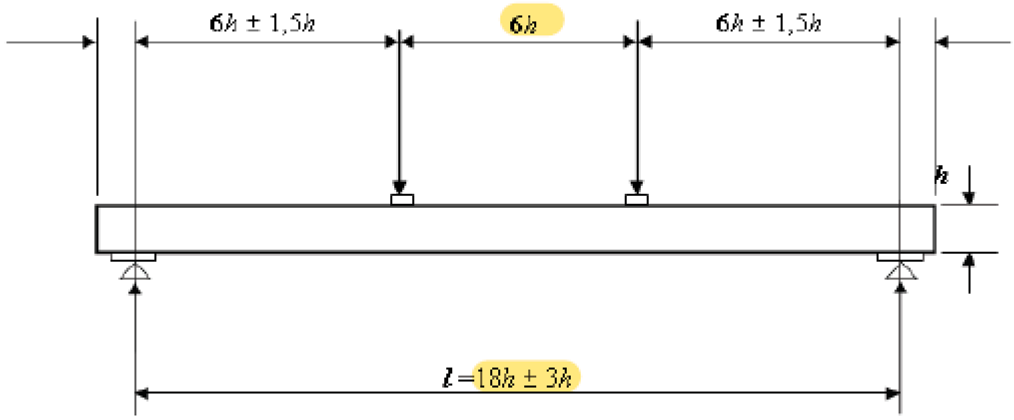


Figure 17 — Test arrangement for measuring bending strength

Figure 46: EN 408:2010-12

<u>Conclusion:</u>

The possibility of the reduced span as per EN 408, Figure 46 above, is beneficial for considering local testing of the glulam samples.

EN 15425:2017: Adhesives - One component polyurethane (PUR) for load-bearing timber structures - Classification and performance requirements

<u>Description:</u>

‘This European Standard establishes a classification for one component polyurethane (PUR) adhesives according to their suitability for use in load-bearing timber structures in defined climatic exposure conditions; it specifies performance requirements for such adhesives for the factory manufacture or factory-like manufacturing of load-bearing timber structures only’.

Source: EN 15425:2017, accessed 27th October 2020.

<u>Relevant findings:</u>

This standard refers to a wide range of tests required of the glue in glulam, rather than the bonding properties of the glulam itself. Most samples must be made specifically for these tests and cannot be cut from the glulam. For many tests, the glue line has to be thick (0.5 or 1mm). Figure 47 below shows the referenced standards required to be applied in the use of EN 15425.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

EN 302-1, *Adhesives for load-bearing timber structures - Test methods - Part 1: Determination of bond strength in longitudinal tensile shear strength*

EN 302-2, *Adhesives for load-bearing timber structures - Test methods - Part 2: Determination of resistance to delamination*

EN 302-3, *Adhesives for load-bearing timber structures - Test methods - Part 3: Determination of the effect of acid damage to wood fibres by temperature and humidity cycling on the transverse tensile strength*

EN 302-4, *Adhesives for load-bearing timber structures - Test methods - Part 4: Determination of the effects of wood shrinkage on the shear strength*

EN 923:2005, *Adhesives - Terms and definitions*

EN 1995-1-1, *Eurocode 5: Design of timber structures – Part 1-1: General - Common rules and rules for buildings*

EN 15416-2, *Adhesives for load bearing timber structures other than phenolic and aminoplastic - Test methods - Part 2: Static load test of multiple bondline specimens in compression shear*

EN 15416-3, *Adhesives for load bearing timber structures other than phenolic and aminoplastic - Test methods - Part 3: Creep deformation test at cyclic climate conditions with specimens loaded in bending shear*

EN 15416-4, *Adhesives for load bearing timber structures other than phenolic and aminoplastic - Test methods - Part 4: Determination of open assembly time for one component polyurethane adhesives*

EN 15416-5, *Adhesives for load bearing timber structures other than phenolic and aminoplastic - Test methods - Part 5: Determination of conventional pressing time*

Figure 47: EN 15425:2017, pg. 4

Conclusion:

The most relevant tests are:

- Shear test 'EN 302-1 Adhesives for load-bearing timber structures — Test methods — Part 1: Determination of longitudinal tensile shear strength'
- Compression time for PUR, EN 15416-5, Adhesives for load-bearing timber structures other than phenolic and aminoplastic – Test methods - Part 5: Determination of conventional pressing time
- Delamination test, EN 302-2 (see 3.12)

Refer to D. Case study for application of the relevant tests from EN 15425.

EN 302-2: 2017: Adhesives for load-bearing timber structures - Test methods - Part 2: Determination of resistance to delamination

Description:

'This European Standard specifies a method for determining the resistance to delamination in glue lines. It is suitable for the following applications: a) for assessing the compliance of adhesives with EN 301, EN 15425 and prEN 16254; b) for assessing the suitability and quality of adhesives for load-bearing timber structures., plus: c) for comparing the effects on the bond strength resulting from the choice of bonding conditions, from different climatic conditioning and from the treatment of the test pieces before and after bonding'.

Source: EN 302-2:2017, accessed 27th October 2020.

Relevant findings:

Specimens have to be produced specifically for this test in contrast to AS 1328.1 and EN 14080 in which the samples are cut from the glulam.

The initial test is performed in accordance with EN 14080, table 15, in which EN 302-2 is a requirement. It is not for the Factory Production Control (FPC) test (also known as Routine test).

All wood species are covered, and the wood species that is intended to be used for the glulam has to be tested. As per the section D. Case study, plantation *E. nitens* could be tested.

There are two types of test: one test for adhesive type II and the other harsher test for adhesive Type I.

This standard also describes the test for a glue line of 2mm thickness.

Test parameters for testing the samples, as shown in Figure 48 below, are similar to those in AS 1328.1 and EN 14080. However, they differ in the pressure, time and the number of cycles.

Table 2 — Cyclic treatments for the delamination test

Treatment	Parameters	Units	High temperature procedure for Type I adhesive	Low temperature procedure for Type II adhesive
Water impregnation	Water temperature	°C	10 to 25	10 to 25
	Absolute pressure	kPa	25 ± 5	25 ± 5
	Duration	min	15	15
	Absolute pressure	kPa	600 ± 25	600 ± 25
	Duration	h	1	1
	Nr impregnation cycles	-	2	2
Drying	Air temperature	°C	65 ± 3	27,5 ± 2,5
	Air humidity	%	12,5 ± 2,5	30 ± 5
	Air circulation[a]	m/s	-	-
	Duration	h	20 ± 2	90 ± 6
	Number of complete cycles (A cycle consists of two water impregnation treatments and one drying treatment.)	-	3	2

[a] Air circulation of 2 m/s to 3 m/s in empty chamber has proven to be suitable.

Figure 48: EN 302-2:2017, pg. 10

<u>Conclusion:</u>

The test detailed in EN 302-2 is for an initial test, and test principles are similar to AS 1328.1 and EN 14080.

The specimens have to be produced specifically for this test in contrast to AS 1328.1 and EN 14080 in which the samples are cut from the glulam.

With regard to D. Case study, it is recommended to conduct the delamination test in accordance with this standard EN 302-2, unless the glue producer can make this test.

Recommended equipment:

Procurement of an autoclave or other device that allows delamination tests (partial vacuum and overpressure).

It is noted that if the test, according to this standard, is not performed, the delamination test according to AS 1328.1 or EN 14080 Annex C should be performed using the corresponding apparatus.