forests

Article

Rolling Shear Properties of Cross-Laminated Timber Made from Australian Plantation *Eucalyptus nitens* under Planar Shear Test

Azin Ettelaei [1,*], Assaad Taoum [2], Jon Shanks [2] and Gregory Nolan [1]

[1] Centre for Sustainable Architecture with Wood, University of Tasmania, Launceston, TAS 7250, Australia; gregory.nolan@utas.edu.au
[2] School of Engineering, College of Sciences and Engineering, University of Tasmania, Hobart, TAS 7005, Australia; assaad.taoum@utas.edu.au (A.T.); jon.shanks@utas.edu.au (J.S.)
* Correspondence: azin.ettelaei@utas.edu.au

Abstract: With the increasing availability of fast-growing *Eucalyptus* plantation logs in Australia in recent years, the timber manufacturing sector has become interested in discovering the opportunities of producing value-added timber products from this resource. Cross-laminated timber (CLT) could be a potential sustainable product recovered from this resource and supply material for commercial buildings. Shear of the inner cross-laminates, known as rolling shear, is one of the governing factors in serviceability and limit state design for this product under out-of-plane loading. This study evaluated the rolling shear (RS) properties of CLT with heterogonous layup configurations using different structural grade *Eucalyptus nitens* (*E. nitens*) timber under the planar shear test. Based on the results, G_r and τ_r values were shown to be significantly correlated with the density of the CLT panel. There was also a positive correlation between the RS modulus and MOR of the CLT panel. The specimens with high MOE in the top and bottom layers indicated the highest τ_r and F_{max} values. This indicated that using high-grade boards in the top and bottom lamellae plays an important role in increasing the RS strength, whereas using them in the cross-layer has a positive contribution in increasing shear modulus. The maximum observed RS strength and modulus ranged from 2.8–3.4 MPa and 54.3–67.9 MPa, respectively, exceeding the RS characteristic values of the resource. The results obtained in this study were comparable to those recommended in European standards for softwood CLT, demonstrating the potential use for eucalypt timber boards in CLT production. This paper provides an important insight into supporting the potential engineering applications of CLT panel products fabricated with eucalypt plantation.

Keywords: rolling shear; cross-laminated timber (CLT); hardwood plantation; *Eucalyptus nitens*; planar shear test; structural properties

Citation: Ettelaei, A.; Taoum, A.; Shanks, J.; Nolan, G. Rolling Shear Properties of Cross-Laminated Timber Made from Australian Plantation *Eucalyptus nitens* under Planar Shear Test. *Forests* **2022**, *13*, 84. https://doi.org/10.3390/f13010084

Academic Editors: Diego Elustondo and Leonardo da Silva Oliveira

Received: 3 December 2021
Accepted: 4 January 2022
Published: 7 January 2022

1. Introduction

The majority of Australia's hardwood plantations (over 884,000 ha) are *Eucalyptus* genus, and almost 29.5 million cubic metres were harvested during the period 2019–2020 [1]. The majority of this hardwood plantation has been managed for pulpwood application [2]. Given its scale, timber producers are seeking to recover value-added timber products from this resource to potentially replace imports and create new markets for plantation hardwood timber in the Australian building sector. According to the forest product annual review, the global production capacity of CLT in recent years is estimated at 2.8 million cubic meters in the world, and new development in this sector has been taking place [3]. In recent years, Australian producers have considered the potential for using fast-growing *Eucalyptus nitens* (*E. nitens*) plantation resources to generate a feedstock for structural mass-laminated timber production, especially for cross-laminated timber (CLT) panel. However, the timber sawn from this resource contains a significant amount of strength reducing characteristics (SRCs), which increase variability in its mechanical properties and limit the sawn board's utility in structural application [4,5]. Incorporating this material in CLT provides the possibility of converting a potential grade material at an individual board level into a high-value assembled product with useful and reliable structural properties. Due to orthogonal layup, CLT mitigates the impact of individual SRCs and provides more uniform mechanical and physical properties. Furthermore, CLT has other advantages, including high carbon sequestration, minimal waste due to prefabrication and lightweight properties in structure [6,7]. This makes CLT suitable for use in load-bearing structural elements such as floor, roof and shear wall components [7]. CLT was developed from softwood species in the European construction market in the early 1990s [8,9]. Spruce–pine–fir and Norway spruce are the common types of species for CLT manufacturing in North America and Europe, respectively [9]. Manufacturing CLT panels has provided many benefits to the timber industry by turning low-value products from eucalypt plantations into a practical product. Several recent studies reported that CLT manufactured from eucalypt species, i.e., *E. nitens*, *E. globulus*, *E. grandis*, *E. urophylla*, demonstrated adequate mechanical properties for a range of structural applications [10–12].

Shear stress, known as rolling shear, has been considered as a potential issue in the perpendicular plane that can control the performance of CLT for structural application, which needs to be considered in ultimate and serviceability limit state design [13–15]. The overall shear performance and global deflection of the panel depend on the rolling shear properties of the cross-layer when the CLT element is subjected to out-of-plane bending.

A comprehensive understanding of rolling shear (RS) strength and modulus (G_R) is therefore crucial to the design of CLT structures. Previous research on rolling shear properties is limited to European species, i.e., Norway spruce, European beech (*Fagus sylvatica* L.) and other species such as Australian Radiata pine, Poplar-beech, yellow pine and eastern hemlock [13,16–18]. Ehrhart & Brandner [13] investigated the effect of timber species (six species including hardwood and softwood), sawing pattern and layup geometry on rolling shear properties. Their outcomes indicated that sawing pattern and width to thickness ratio of the lamella could influence the shear properties. They also reported the mean value of RS strength and shear modulus for Norway spruce as 1.88 MPa and 100 MPa, respectively. However, RS strength and modulus values for hardwood species, i.e., European ash and beech, were significantly higher than the softwood values, reported as 5.40 MPa and 350 MPa, respectively. Ettelaei et al. [19] evaluated the rolling shear properties of CLT made from Australian *E. nitens* and *E. globulus* plantation under short-span three-point bending test. These researchers indicated the influence of the modulus of elasticity (MOE) of sawn timber in the top and bottom layer of CLT on RS properties. They obtained RS values for high-grade *E. nitens* and *E. globulus* of 2.0 MPa and 2.2 MPa and values for low-grade material of 1.8 MPa and 2.1 MPa, respectively. In a study investigating the shear performance of the Australian radiata pine CLT, the maximum shear stress values were reported from 1.55 MPa to 2.18 MPa [20]. The characteristics of rolling shear strength and modulus for Australian pine CLT were reported as 2.0 MPa and 65.5 MPa, respectively [16].

Despite these studies [13,16,21–24], limited research has evaluated the rolling shear properties and the influencing parameters on the shear performance of CLT from eucalyptus plantation resources. Therefore, it is necessary to investigate the mechanical properties of mass timber elements governed by serviceability limit state for their structural applications. Different approaches and configurations have been used to determine the rolling properties of the CLT [13]. The test setup used in this study is reported as a suitable and accurate method compared to other methods available for determining rolling shear properties [11,14,19]. This research is now necessary because Tasmanian manufacturers are now using local fibre-managed plantation *E. nitens* to produce CLT panels for the Australian market. Given this market development and the knowledge gap, this study investigates the rolling shear properties and failure modes of three-layer CLT with different layup configurations under the planar shear test. The CLT panels used in this study have heterogeneous configurations using a combination of structural grades (7 GPa to 21 GPa) in the panel lamella to maximise lower-grade material utilisation and improve efficiency from timber processing. The main aim of this research was to evaluate the rolling shear properties of CLT with heterogenous layup configuration under the planar shear test. This study also investigates the effect of lamination MOE on the RS strength of CLT panels.

The results were analysed to investigate the potential of using hardwood *E. nitens* CLT elements for structural purposes. The results were compared with those obtained from short-span bending tests in the previous research, demonstrating good agreement for Australian CLT produced from *E. nitens* plantation. The results of this study provide an important insight into developing high-value Australian-made CLT from pulpwood *E. nitens* timber resource for structural application.

2. Materials and Methods

2.1. Material

The timber used in this research was sourced from 21-year-old fibre-managed plantation *E. nitens* in southern Tasmania, Australia, dried to a nominal moisture content (MC) of 12% and with an average oven-dry density of 569.9 ± 53.7 kg/m^3. The modulus of elasticity (MOE) of all boards was obtained in the linear elastic range under four-point bending test using Calibre STFE10 Machine according to AS/NZS 4063.1 [25]. The average MOE and MOR values of the material were determined as 13.8 ± 2.58 GPa and 60 ± 21.3 GPa, respectively.

2.2. CLT Panel Manufacturing

The three-layer CLT panels with four types of panel configuration were then produced under the manufacturing condition at CUSP Building Solutions, Wynyard, Tasmania, Australia. For each configuration, three full-size panels were manufactured and bonded with one-component polyurethane structural adhesive (LOCTITE HB S309). No edge gluing was applied. The code of each specimen is associated with the code number of the sample and layer configuration based on grade, respectively. The average values of the MOE of the boards used in the panel layup from the top to bottom layers of the CLT panels are presented in Table 1 The bending stiffness and apparent MOE appear to have significant differences between different layup configurations, i.e., MOE of each layer. The panel configuration with high-grade boards in the top and bottom layer exhibited the highest average bending stiffness values, followed by the configuration with high-grade boards in the bottom layer compared to other specimens. The results also indicated that the MOE of boards used in the transverse layers has a negligible contribution to bending stiffness. All relevant bending properties of the tested full-scale CLT panel under four-point bending are summarised in Table 1. It is worth noting that the bending properties of the tested CLT are not the focus of this research.

The maximum shear strength of the full-scale CLT panels was calculated using the analytical method [22,24,26] as follow:

$$\tau_{max} = \frac{V_{max}\,Q}{IB} \quad (1)$$

where V_{max} is the maximum shear force (kN), Q is the first moment of area (mm^3), I is the moment of inertia and b is the width of the cross-section (mm).

Table 1. Summary of CLT panel properties and bending test results.

Species	Panel Code	Lamination Grade from Top to Bottom	Average MOE of Individual Layup (GPa)	Apparent MOE of the Panel (GPa)	MOR (N/mm^2)
E. nitens	CL1/MHM-1	Medium	13.4	12.8	66.1
	CL1/MHM-2	High	16.2	13.0	72.3
	CL1/MHM-3	Medium	13.7	12.9	69.3
	CL2/MLH-1	Medium	13.4	13.9	73.5
	CL2/MLH-2	Low	10.8	13.9	65.0
	CL2/MLH-3	High	16.7	14.2	61.7
	CL3/MLM-1	Medium	13.4	12.7	60.7
	CL3/MLM-2	Low	10.8	13.2	54.2
	CL3/MLM-3	Medium	13.6	12.8	49.9
	CL4/HLH-1	High	16.6	15.7	72.6
	CL4/HLH-2	Low	10.4	15.9	73.7
	CL4/HLH-3	High	16.7	15.3	50.0

2.3. Experimental Setup

2.3.1. Planar Shear Specimen Preparation

From each of the CLT panel configurations, 18 planar shear specimens (6 specimens per CLT panel) with dimensions of 80 × 99 × 250 mm (b × h × l) were extracted. There are limited standard test methods and configurations for evaluating the rolling shear properties of a CLT panel [21,26–28]. In this study, the planar shear test was conducted using the method developed and suggested by previous researchers [26–28] and tested under EN408 standard [28]. This test setup is based on the configuration recommended by EN408 and modified and performed with different sizes of specimens and different inclinations and parameters. The suitability of the test configuration is confirmed by previous researchers [24,29]. Grasshopper for Rhino 3d [30] was used to parametrically determine the appropriate cutting angle for the rolling shear test. The method was to create a parametric box to represent shear samples of the proper size. A line was then drawn between opposite corners, and its angle from the vertical was measured. The box could then be rotated to show the sample, and any further cuts are displayed in Figure 1a. The inclination angle of the samples was calculated based on its dimensions (length and width), given that the optimal angle to test and be vertically fixed under the test rig was obtained as specified in EN408 [28] (Figure 1b). The shear sample designation and the average values of MOE of each lamination in the top, cross and bottom layers of the shear test specimens are specified in Table 2.

2.3.2. Rolling Shear Test

The shear test was performed using a 500 kN Avery Universal Testing Machine with a 0.5 mm/min loading rate. The specimens were loaded to failure, and LVDT was used to measure the displacement. The shear specimens were vertically adjusted between two small rectangular steel plates to minimise crushing and premature failure. The experimental test setup is demonstrated in Figure 1c. The shear modulus (G) and rolling shear strength were calculated using Equations (2) and (3), respectively:

$$\tau_R = \frac{p_{max} \times \cos\alpha}{L \times w} \tag{2}$$

$$G_R = \frac{t_{cross}}{L \times w} \times \frac{p_{max}}{\Delta} \times \cos(\alpha) \tag{3}$$

where P_{max} is the maximum load (kN), L is the specimen length, w is the specimen width, t_{cross} is the cross-layer thickness, α is the inclination angle and $\frac{p}{\Delta}$ is calculated from the load-defection curve between 0.1 and 0.4 P points.

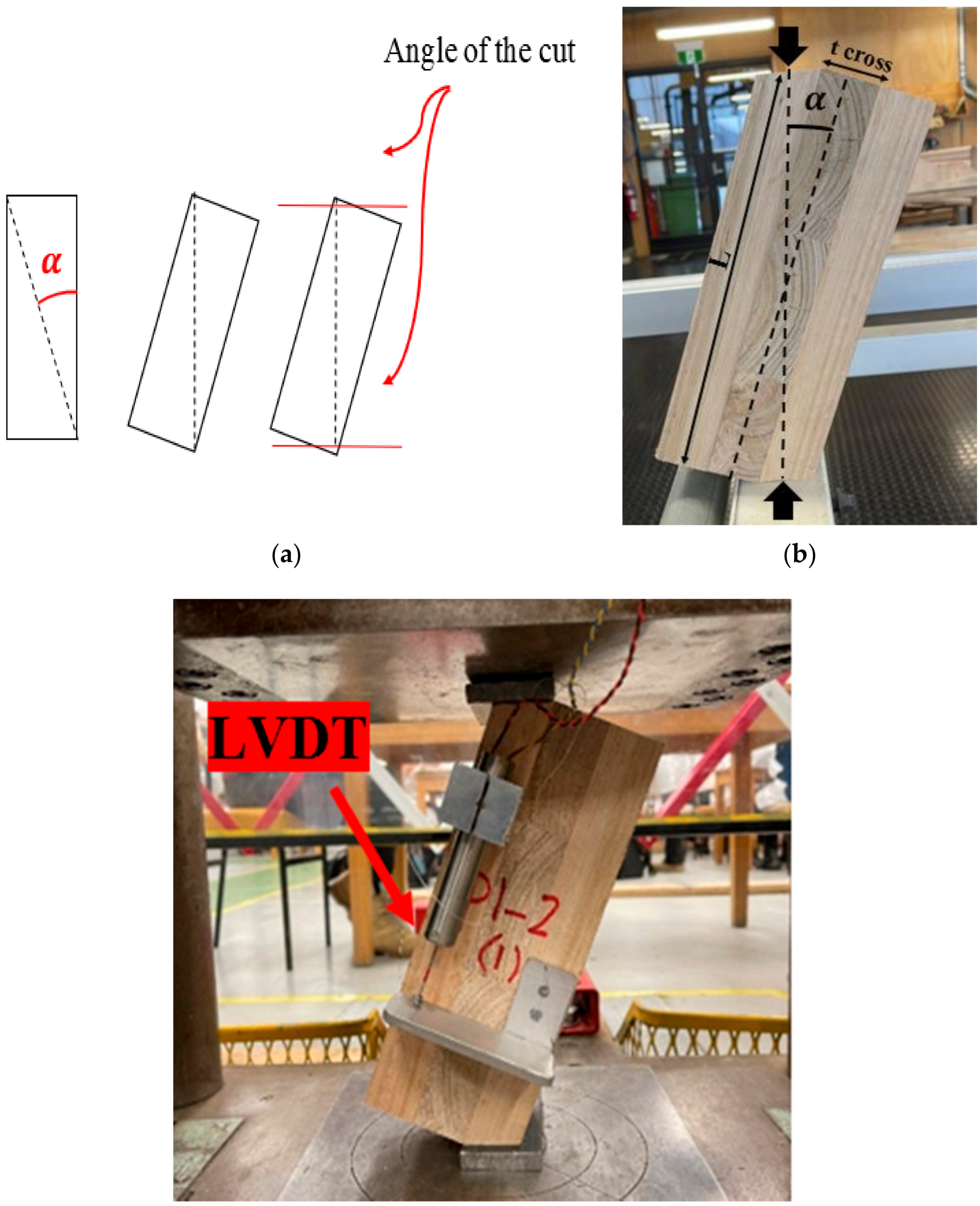


Figure 1. Test configuration for the planar shear test. (**a**) Specimens geometry, (**b**) Test specimen, (**c**) Test specimens during testing.

Table 2. Detail of sample for planar shear test.

Specimen Code	MOE [a]	N [b]	Specimen Code	MOE	N	Specimen Code	MOE	N	Specimen Code	MOE	N
RS-MHM	13.4 16.2 13.7	18	RS-MLH	13.4 10.8 16.7	18	RS-MLM	13.4 10.8 13.6	18	RS-HLH	16.6 10.4 16.7	18

[a] Average MOE of individual lamination from top to bottom (GPa). [b] Number of specimens.

3. Data Evaluation

Statistical analysis of the effects of the test variables on rolling shear properties was performed using R software with R studio. One-way analysis of variance (ANOVA) was carried out to compare the mean values of rolling shear properties of the four-specimen group. Duncan's Multiple Range Test was used to compare the average values of variables obtained in each configuration group.

4. Results

The statistical analyses of the effect of the test variables on the rolling shear properties are detailed in Table 3. The HLH specimens indicated the highest rolling shear strength among the tested groups, with higher MOE in the top and bottom layers. The difference in τ_r values between groups were statistically significant when compared to those obtained by HLH and both MLH and MLM configuration based on Duncan's test results. This can be attributed to the higher average MOE of timber boards used in the top and bottom lamination compared to the other configuration. The difference in the mean rolling shear strength values between four panel configurations can be observed in Figure 2. The G_r value for the MHM specimens made of higher-grade sawn timber in the cross-layer was, on average, 7.6% higher than specimens MLH and HLH and 11% higher than MLM specimens, although this was statistically different only from that obtained by MLM specimens. Such differences in the results between the two MLM and MHM specimens could be due to the effect of the MOE of the sawn boards used in the cross-layer of the panel on the shear modulus of the specimens.

Table 3. Mean values of different variables from the test specimens.

Panel Type	N	G_r (MPa)	SD	Duncan's Group	COV (%)
RS-MHM	18	67.9	14.9	B	21.9
RS-MLH	18	57.9	22.3	AB	38.5
RS-MLM	18	54.3	14.8	A	27.2
RS-HLH	18	58.5	13.2	AB	22.5
		τ_r(MPa)			
RS-MHM	18	3.1	0.5	AB	16.1
RS-MLH	18	2.8	0.4	A	14.2
RS-MLM	18	2.9	0.6	A	20.6
RS-HLH	18	3.4	0.5	B	14.7
		F_{max} (kN)			
RS-MHM	18	67.3	10.0	AB	14.8
RS-MLH	18	60.7	9.5	A	15.6
RS-MLM	18	61.6	13.0	A	21.1
RS-HLH	18	71.9	10.7	B	14.8

As shown in Figure 2, the maximum rolling shear strength average value ranged from 2.8 MPa (MLH specimens) to 3.4 MPa (HLH specimens). These values were higher than those reported in the literature and the value reported for the Australian radiata pine CLT [16,19,20]. The τ_r values were also higher than those reported in a previous study for CLT from Eucalyptus plantation under short span bending [19]. The lowest mean τ_r values obtained in this study (2.82 MPa) were higher than those rolling shear characteristic values (2.0 MPa) reported by Li et al. [16] and the values (1.55 MPa–2.18 MPa) demonstrated by Navaratam et al. [20] for Radiata Australian pine CLT.

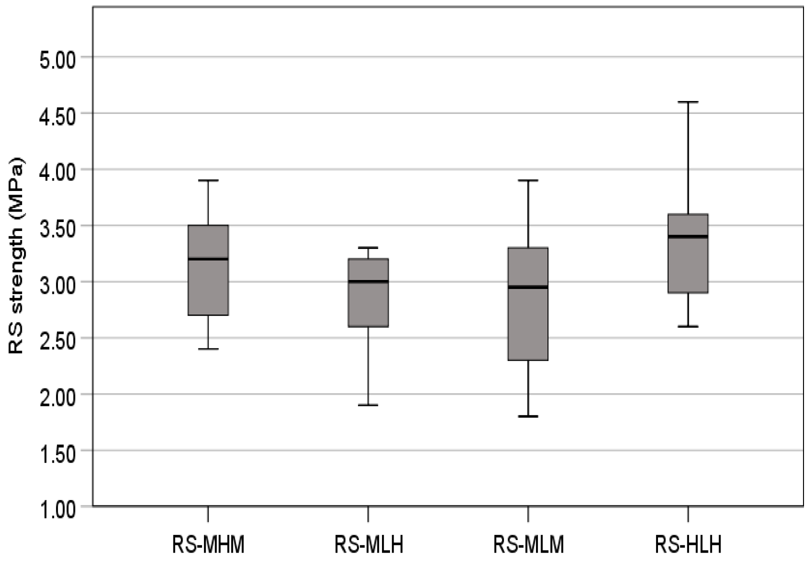


Figure 2. Rolling shear strength for each specimen group.

τ_rThe sawn timber used in those panels had lower average MOE values than the specimens in this study. The correlation between the test variables and the rolling shear properties of the test specimens for all configurations are shown in Table 4. Based on the results presented in this table, both G_r and τ_r values appear to be significantly correlated to the density of the timber boards used in the panel. There was a positive correlation (R^2 = 0.344) between τ_r values and density of the panel. The R^2 obtained for the correlation between G_r and the density of the sawn board used in the CLT panel was 0.579. This is in line with previous research [19]. Previous research has also reported a positive correlation between density and mechanical characteristics of timber [13]. There was also a positive correlation (R^2 = 0.331) between the MOR of the parent panel and G_r values of the specimens. This effect was significant for G_r and insignificant for τ_r values. The ANOVA test results showed that the effect of the MOE of the boards used in the specimens on the τ_r values were highly significant at a ;95% level of confidence (Table 5). This effect was significant for those with different MOE of the timber boards in the outer layers of the specimens. The minimum load obtained was 40 kN, while the maximum was 100 kN; these were for MLM and HLH specimens, respectively.

Table 4. Correlation between the test variables.

		τ_r	G_r	Density	F_{max}	MOR
τ_r	Pearson Correlation	1	0.354	0.587 *	0.994 **	0.415
	Sig. (2-tailed)		0.259	0.045	0.000	0.179
	N	12	12	12	12	12
G_r	Pearson Correlation	0.354	1	0.761 **	0.405	0.576 *
	Sig. (2-tailed)	0.259	-	0.004	0.192	0.05
	N	12	12	12	12	12
Density	Pearson Correlation	0.587 *	0.761 **	1	0.600 *	0.533
	Sig. (2-tailed)	0.045	0.004	-	0.039	0.074
	N	12	12	12	12	12
F_{max}	Pearson Correlation	0.994 **	0.405	0.600 *	1	0.393
	Sig. (2-tailed)	0.000	0.192	0.039	-	0.206
	N	12	12	12	12	12
MOR	Pearson Correlation	0.415	0.576 *	0.533	0.393	1
	Sig. (2-tailed)	0.179	0.05	0.074	0.206	-
	N	12	12	12	12	12

* Correlation is significant at the 0.05 level (2-tailed). ** Correlation is significant at the 0.01 level (2-tailed).

Table 5. ANOVA test results on the impact MOE of specimen lamellae on shear properties.

Source	Dependent Variables	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	F_{max}	1507.5	3	502.5	4.2	0.009
	G_r	1837.5	3	612.5	2.2	0.096
	τ_r	3.2	3	1.1	4.2	0.008
Intercept	F_{max}	307,720.1	1	307,720.1	2582.9	0.000
	G_r	256,208.7	1	256,208.7	919.7	0.000
	τ_r	667.3	1	667.3	2616.9	0.000
Group	F_{max}	1507.5	3	502.5	4.2	0.009
	G_r	1837.5	3	612.5	2.2	0.096
	τ_r	3.2	3	1.1	4.2	0.008
Error	F_{max}	8101.4	68	119.1		
	G_r	18,942.8	68	278.6		
	τ_r	17.3	68	0.3		
Total	F_{max}	317,329.0	72			
	G_r	276,989.0	72			
	τ_r	687.9	72			

4.1. Comparisons of the Results Obtained from Tested Panels and Planar Shear Specimens

The maximum shear strength values for the tested CLT panel obtained from Equation (1) are compared with those obtained from planar shear specimens for all configurations and demonstrated in Figure 3. Because six shear specimens were prepared from each panel, the average shear strength values of the specimen were calculated and compared to those obtained from each CLT panel. The results show a good agreement between the shear strength value of the tested CLT panels and the shear specimens. In most cases, the shear specimens had higher shear strength than the CLT panel, which is attributed to being subjected to shear without global bending. Nevertheless, regardless of configuration and specimen type, comparable average values of 2.7 MPa and 3.0 MPa were obtained for all configurations from the parent CLT panel and planar shear test, respectively.

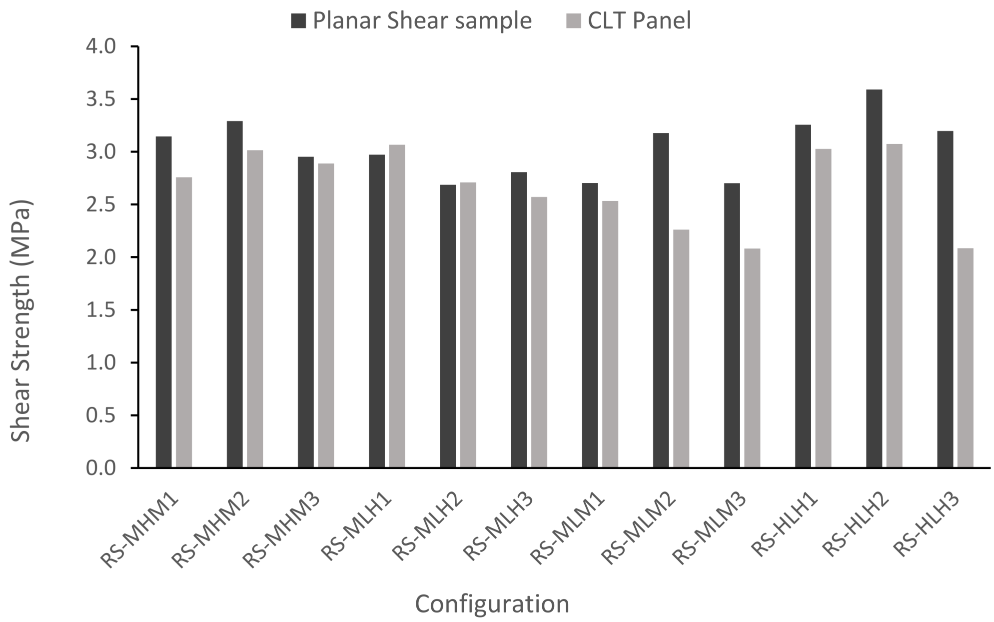
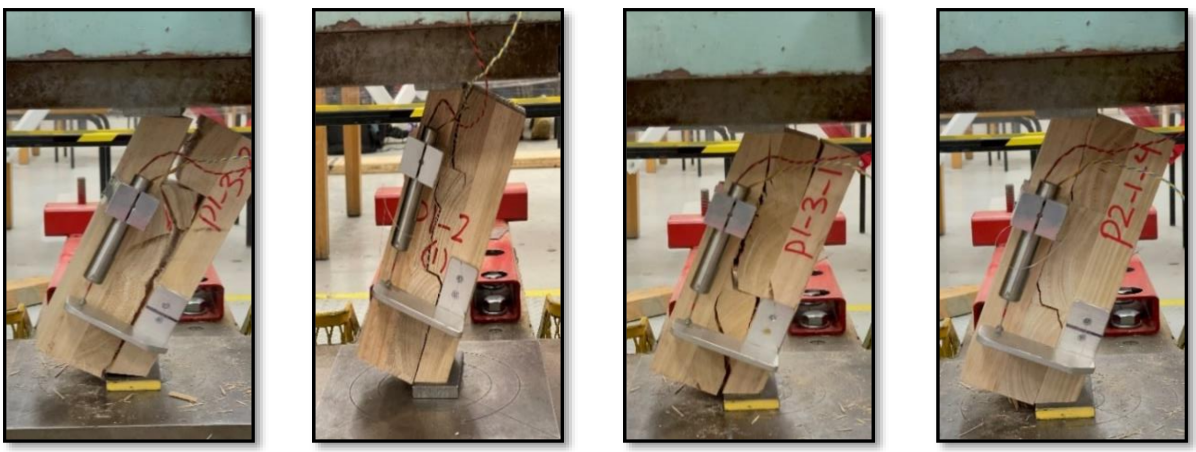


Figure 3. Average shear strength of the CLT panel vs. average shear strength of planar specimens.

4.2. Failure Modes

The typical failure modes observed for the specimens are illustrated in Figure 4. The specimens demonstrated rolling shear failure and had similar failure modes, as shown in Figure 4. Some of the samples failed abruptly at the end of the planar test. Some of the cracks initiated from the interface of the adjacent layer and then propagated along the growth ring in the cross-layer and continued along the entire cross-layer, causing bond line failure (Figure 4a,e). As can be seen, the cracks started from the wood fibre and then propagated through the cross-layer and developed to one side of the glue line. Some specimens exhibited the combination of rolling shear and rupture in the left-side lamella and developed to the glue line in the right lamella (Figure 4c). The results highlight that the dominant failure mode is rolling shear and a combination of shear and delamination. The failure modes of the four specimen configurations were quite similar. All results obtained from the planar tested specimens are summarised in Table A1.



(**a**) (**b**) (**c**) (**d**)

Figure 4. *Cont.*

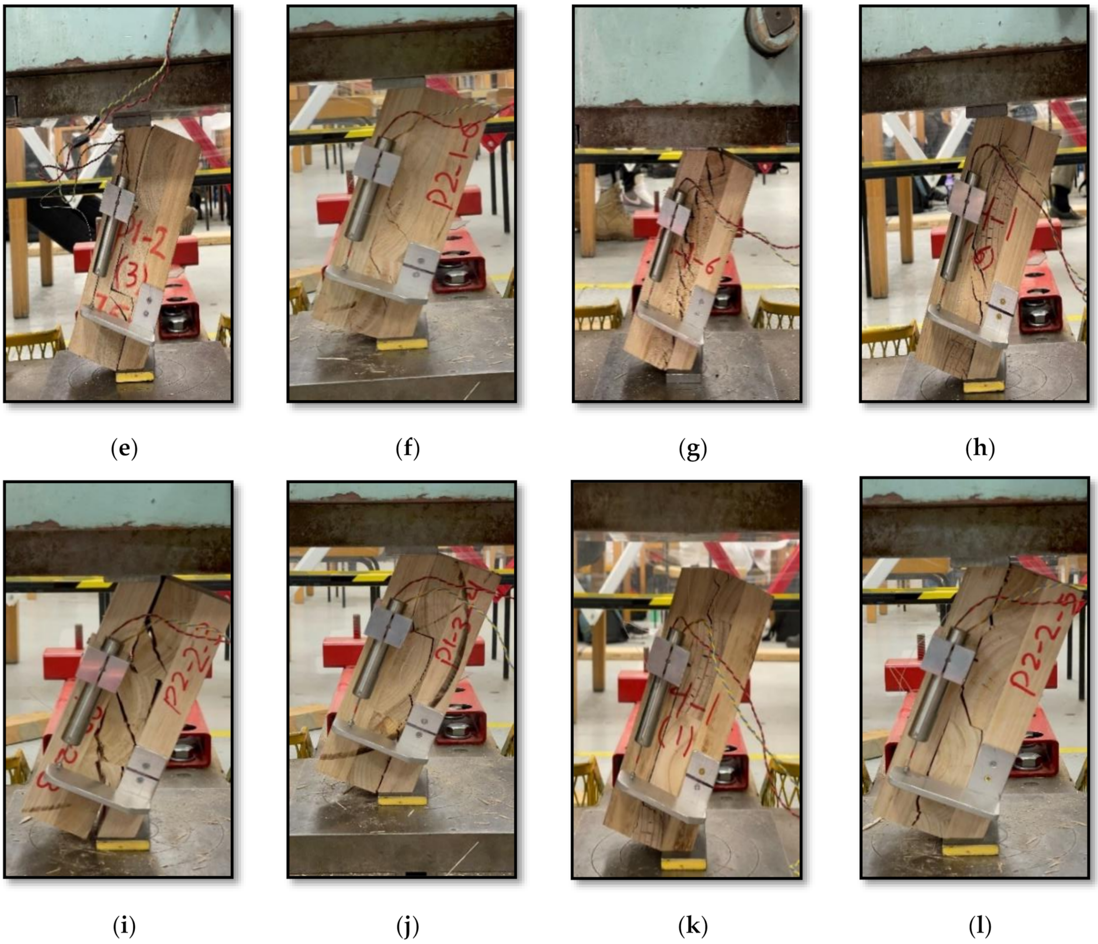


Figure 4. Failure modes of planar shear specimens; (**a**–**c**,**e**,**j**) are RS-MHM;(**d**,**f**,**i**,**l**) are RS-MLH; (**g**) is RS-MLM; (**h**,**k**) are RS-HLH configurations.

5. Discussion

This work investigated the RS properties of heterogenous CLT panels made from *E. nitens* plantation conducted on CLT block specimens under planar shear test. Rolling shear is one of the governing factors in serviceability and limits state design when CLT elements are subjected to out-of-plane bending. This test approach was recommended by EN408; it has been modified based on specimen configuration and size and has been approved as a suitable method for evaluating shear properties. The influence of the MOE of the top and bottom lamellae on the RS strength of CLT blocks was found to be significant. However, the effect of cross-layer MOE was only significant for the RS modulus. Similar to previous research [19], the results demonstrated that the τ_r and G_r values were significantly correlated to the density of the timber boards used in the specimens. There was also a significant correlation (R^2 = 0.331) between the panel MOR and G_r values of the shear specimens; however, this effect was insignificant for rolling shear strength values. The prevalent failure mode of the specimens was rolling shear. Based on the results, the average τ_r values of the planar shear specimens were higher than those τ_r values obtained from *E. nitens* CLT under short span three-point bending test in previous research [19]. Furthermore, the planar shear specimen results were consistent with those shear strength values from the CLT panel, and in all cases, shear specimens had higher shear strength values than the CLT panel. In addition, the results of shear specimens were higher than those parent panels. This may be because CLT blocks were subjected to shear without global bending in the planar shear test. Further parametric analysis to obtain a clear understanding of other effective parameters on the rolling shear properties of *E. nitens* CLT are required. The mean RS strength and modulus values in this study ranged from 2.8 MPa to 3.4 MPa and 54.3 MPa to 67.9 MPa for the different groups of planar shear specimens, respectively. These values exceed the rolling shear characteristic (G_r = 53 MPa and τ_r = 2.0 MPa) of the resource [31]. The RS strength values also were higher than the recommended values in the European standards (1.1 MPa) for softwood CLT [32] and reported values in the published literature [16,20,33] for Australian radiata pine (2.0 MPa) and Norway Spruce (1.7 MPa). These values were also comparable with those in the literature for CLT made of Australian *E. nitens* species under the modified planar shear test method [33]. The results also demonstrated that CLT made from fibre-managed plantation *E. nitens* has satisfactory shear performance to meet serviceability requirement for reliable and structural CLT panels.

6. Conclusions

This study presented novel experimental research performed on CLT blocks under planar shear test to investigate the rolling shear properties of CLT panels made of Australian grown plantation *E. nitens*. The specimens in this study were manufactured from a combination of three MOE-grade groups in panel lamella. This can improve the use of feedstock from Australian grown plantation *E. nitens* and prevent excessive waste from rejecting lower-grade material. The results indicated a statically significant difference in the rolling shear strength between RS-HLH and both RS-MLM and RS-MLH specimens, and in shear modulus, the significant difference was between RS-MLM and RS-MHM specimens. This indicates that high-grade boards in cross-layers have a positive contribution in increasing shear modulus, whereas using them in the top and bottom layer plays an important role in increasing the RS strength. The RS-HLH specimens showed the highest τ_r value, and RS-MHM exhibited the highest shear modulus among other configurations. The RS strength and modulus have also been found to be significantly correlated to the density of the boards used in the panel lamellae. The results indicate that the impact of the MOE of the boards used in the specimen on the rolling shear strength was highly significant at a 95% level of confidence. The maximum RS strength values of all configurations exceeded the rolling shear characteristic of the material and were also comparable with those values in the European and Canadian standards for softwood CLT. The results were also in good agreement with those under short-span bending tests in the literature. The results of this study indicate an overall good shear performance of *E. nitens* CLT panels and provides an important insight into using Australian-made *E. nitnes* CLT panels, demonstrating that they have a great potential for use in a wide range of construction applications.

Author Contributions: Conceptualisation, methodology, A.E.; Testing, A.E. and A.T.; validation, A.E.; formal analysis, A.E.; data curation, A.E.; writing—original draft preparation, A.E.; writing—review and editing, A.E., A.T., J.S. and G.N.; supervision, G.N. and A.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by CoSE Tasmania Graduate Research Scholarship, University of Tasmania, TAS, Australia.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are available from the corresponding author upon reasonable request.

Acknowledgments: The support from the Centre for Sustainable Architecture with Wood (CSAW) and the School of Architecture and Design, University of Tasmania, is highly acknowledged. The authors gratefully acknowledge the School of Engineering at the University of Tasmania for the technical support, especially Calverly Gerard and Andrew Billet for invaluable support in the testing of the material. The authors appreciate the technical support and sample preparation from the CSAW and the University of Tasmania School of Architecture and Design, with acknowledgments to David Tanton and Malcolm Liehr. The invaluable support and advice from Mohammad Derikvand are also gratefully acknowledged.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study, in the collection, analyses, or interpretation of data, in the writing of the manuscript, or in the decision to publish the results.

Appendix A

Table A1. Main results obtained from the planar shear test.

Specimens Code	Configuration	F_{max} (kN)	δ (mm)
RS1-1-1	MHM	70.13	2.29
RS1-1-2	MHM	68.08	2.18
RS1-1-3	MHM	82.94	2.48
RS1-1-4	MHM	56.42	1.89
RS1-1-5	MHM	50.58	2.30
RS1-1-6	MHM	77.49	2.43
RS1-2-1	MHM	74.30	3.27
RS1-2-2	MHM	62.57	3.94
RS1-2-3	MHM	59.02	2.55
RS1-2-4	MHM	64.66	2.43
RS1-2-5	MHM	80.79	3.37
RS1-2-6	MHM	83.06	3.13
RS1-3-1	MHM	58.92	2.65
RS1-3-2	MHM	69.56	2.74
RS1-3-3	MHM	71.90	2.92
RS1-3-4	MHM	70.60	2.75
RS1-3-5	MHM	54.21	2.70
RS1-3-6	MHM	55.60	2.44
RS2-1-1	MLH	70.89	2.84
RS2-1-2	MLH	55.61	2.49
RS2-1-3	MLH	65.87	2.98
RS2-1-4	MLH	70.74	2.94
RS2-1-5	MLH	56.07	2.68
RS2-1-6	MLH	64.07	2.55
RS2-2-1	MLH	68.96	2.58
RS2-2-2	MLH	55.08	1.89
RS2-2-3	MLH	65.14	2.79
RS2-2-4	MLH	63.74	2.65
RS2-2-5	MLH	48.48	2.18
RS2-2-6	MLH	45.01	2.82
RS2-3-1	MLH	64.18	2.37
RS2-3-2	MLH	39.95	2.46
RS2-3-3	MLH	51.87	2.98
RS2-3-4	MLH	67.53	2.65
RS2-3-5	MLH	69.06	3.78
RS2-3-6	MLH	69.25	3.08
RS3-1-1	MLM	60.85	2.41
RS3-1-2	MLM	40.50	1.96
RS3-1-3	MLM	83.86	3.70
RS3-1-4	MLM	74.58	2.67
RS3-1-5	MLM	46.37	2.37
RS3-1-6	MLM	42.33	2.89
RS3-2-1	MLM	72.17	2.36
RS3-2-2	MLM	62.63	3.17
RS3-2-3	MLM	64.74	2.05
RS3-2-4	MLM	71.26	2.56
RS3-2-5	MLM	70.06	2.84
RS3-2-6	MLM	68.92	2.94
RS3-3-1	MLM	61.35	2.63
RS3-3-2	MLM	38.78	2.05

Table A1. *Cont.*

Specimens Code	Configuration	F_{max} (kN)	δ (mm)
RS3-3-3	MLM	58.53	2.99
RS3-3-4	MLM	49.72	2.70
RS3-3-5	MLM	73.01	2.55
RS3-3-6	MLM	67.07	2.86
RS4-1-1	HLH	78.91	2.55
RS4-1-2	HLH	74.57	3.27
RS4-1-3	HLH	63.41	2.82
RS4-1-4	HLH	76.34	3.78
RS4-1-5	HLH	63.68	3.10
RS4-1-6	HLH	62.95	3.06
RS4-2-1	HLH	76.30	2.68
RS4-2-2	HLH	73.71	2.31
RS4-2-3	HLH	99.82	3.22
RS4-2-4	HLH	70.02	2.44
RS4-2-5	HLH	59.16	2.24
RS4-2-6	HLH	84.00	2.84
RS4-3-1	HLH	66.13	3.30
RS4-3-2	HLH	72.89	3.15
RS4-3-3	HLH	73.95	2.24
RS4-3-4	HLH	62.26	2.22
RS4-3-5	HLH	55.24	2.72
RS4-3-6	HLH	81.80	4.64

References

1. ABARES. *Australian Forest and Wood Products Statistics: March and June Quarters 2021*; Australian Bureau of Agricultural and Resource Economics and Sciences: Canberra, Australia, 2021.
2. McGavin, R.L.; Bailleres, H.; Hamilton, M.G.; Blackburn, D.P.; Vega, M.; Ozarska, B. Variation in rotary veneer recovery from Australian plantation Eucalyptus globulus and Eucalyptus nitens. *BioResources* **2015**, *10*, 313–329. [CrossRef]
3. UNECE/FAO. *Forest Products Annual Market Review 2019–2020*; UNECE: Geneva, Switzerland, 2020.
4. Derikvand, M.; Kotlarewski, N.; Lee, M.; Jiao, H.; Chan, A.; Nolan, G. Visual stress grading of fibre-managed plantation Eucalypt timber for structural building applications. *Constr. Build. Mater.* **2018**, *167*, 688–699. [CrossRef]
5. Derikvand, M.; Kotlarewski, N.; Lee, M.; Jiao, H.; Chan, A.; Nolan, G. Flexural and visual characteristics of fibre-managed plantation Eucalyptus globulus timber. *Wood Mater. Sci. Eng.* **2018**, *15*, 172–181. [CrossRef]
6. Li, Q.; Wang, Z.; Liang, Z.; Li, L.; Gong, M.; Zhou, J. Shear properties of hybrid CLT fabricated with lumber and OSB. *Constr. Build. Mater.* **2020**, *261*, 120504. [CrossRef]
7. Liu, Y.; Guo, H.; Sun, C.; Chang, W.-S. Assessing Cross Laminated Timber (CLT) as an Alternative Material for Mid-Rise Residential Buildings in Cold Regions in China—A Life-Cycle Assessment Approach. *Sustainability* **2016**, *8*, 1047. [CrossRef]
8. Lim, H.; Tripathi, S.; Li, M. Rolling shear modulus and strength of cross-laminated timber treated with micronised copper azole type C (MCA-C). *Constr. Build. Mater.* **2020**, *259*, 120419. [CrossRef]
9. Dong, W.; Wang, Z.; Zhou, J.; Gong, M. Experimental study on bending properties of cross-laminated timber-bamboo composites. *Constr. Build. Mater.* **2021**, *300*, 124313. [CrossRef]
10. Pangh, H.; Hosseinabadi, H.Z.; Kotlarewski, N.; Moradpour, P.; Lee, M.; Nolan, G. Flexural performance of cross-laminated timber constructed from fibre-managed plantation eucalyptus. *Constr. Build. Mater.* **2019**, *208*, 535–542. [CrossRef]
11. Liao, Y.; Tu, D.; Zhou, J.; Zhou, H.; Yun, H.; Gu, J.; Hu, C. Feasibility of manufacturing cross laminated timber using fast-grown small diameter eucalyptus lumbers. *Constr. Build. Mater.* **2017**, *132*, 508–515. [CrossRef]
12. Dugmore, M.; Nocetti, M.; Brunetti, M.; Naghizadeh, Z.; Wessels, C.B. Bonding quality of crosslaminated timber: Evaluation of test methods on Eucalyptus grandis panels. *Constr. Build. Mater.* **2019**, *211*, 217–227. [CrossRef]
13. Ehrhart, T.; Brandner, R. Rolling shear: Test configurations and properties of some European soft- and hardwood species. *Eng. Struct.* **2018**, *172*, 554–572. [CrossRef]
14. O'Ceallaigh, C.; Sikora, K.; Harte, A. The Influence of Panel Lay-Up on the Characteristic Bending and Rolling Shear Strength of CLT. *Buildings* **2018**, *8*, 114. [CrossRef]
15. Karacabeyli, E.; Douglas, B. CLT handbook: Cross-laminated timber, US edition, FPInnovations. *Can. J. Fish. Aquat. Sci.* **2013**, *70*, 59.
16. Li, X.; Ashraf, M.; Subhani, M.; Kremer, P.; Li, H.; Anwar-Us-Saadat, M. Rolling shear properties of cross-laminated timber (CLT) made from Australian Radiata Pine–An experimental study. *Structures* **2021**, *33*, 423–432. [CrossRef]

17. Cao, Y.; Street, J.; Li, M.; Lim, H. Evaluation of the effect of knots on rolling shear strength of cross laminated timber (CLT). *Constr. Build. Mater.* **2019**, *222*, 579–587. [CrossRef]
18. Kaboli, H.; Clouston, P.L.; Lawrence, S. Feasibility of Two Northeastern Species in Three-Layer ANSI-Approved Cross-Laminated Timber. *J. Mater. Civ. Eng.* **2020**, *32*, 04020006. [CrossRef]
19. Ettelaei, A.; Taoum, A.; Nolan, G. Rolling shear properties of cross-laminated timber made of fibre-managed plantation eucalyptus under short-span bending. *Wood Mater. Sci. Eng.* **2021**, 1–8. [CrossRef]
20. Navaratnam, S.; Christopher, P.B.; Ngo, T.; Le, T.V. Bending and shear performance of Australian Radiata pine cross-laminated timber. *Constr. Build. Mater.* **2020**, *232*, 117215. [CrossRef]
21. Wang, R.; Shi, J.J.; Xia, M.K.; Li, Z. Rolling shear performance of cross-laminated bamboo-balsa timber panels. *Constr. Build. Mater.* **2021**, *299*, 123973. [CrossRef]
22. Li, X.; Ashraf, M.; Subhani, M.; Kremer, P.; Kafle, B.; Ghabraie, K. Experimental and numerical study on bending properties of heterogeneous lamella layups in cross laminated timber using Australian Radiata Pine. *Constr. Build. Mater.* **2020**, *247*, 118525. [CrossRef]
23. Wang, Z.; Zhou, J.; Dong, W.; Yao, Y.; Gong, M. Influence of technical characteristics on the rolling shear properties of cross laminated timber by modified planar shear tests. *Maderas. Cienc. Y Tecnol.* **2018**, *20*, 469–478. [CrossRef]
24. Ehrhart, T.; Brandner, R.; Schickhofer, G.; Frangi, A. Rolling shear properties of some European timber species with focus on cross laminated timber (CLT): Test configuration and parameter study. In *International Network on Timber Engineering Research 2015: Proceedings of Meeting 48*; Timber Scientific Publishing, KIT Holzbau und Baukonstruktionen: Karlsruhe, Germany, 2015; pp. 61–76. [CrossRef]
25. Standards Australia. Standards New Zealand AS/NZS 4063.1:2010 Structural Timber—Characteristic Values of Strength Graded Timber. Standards Australia and Standards New Zealand: Sydney, Australia; Wellington, New Zealand, 2010.
26. Hematabadi, H.; Madhoushi, M.; Khazaeian, A.; Ebrahimi, G. Structural performance of hybrid Poplar-Beech cross-laminated-timber (CLT). *J. Build. Eng.* **2021**, *44*, 102959. [CrossRef]
27. Gui, T.; Cai, S.; Wang, Z.; Zhou, J. Influence of Aspect Ratio on Rolling Shear Properties of Fast-Grown Small Diameter Eucalyptus Lumber. *J. Renew. Mater.* **2020**, *8*, 53–1066. [CrossRef]
28. *BS EN 408*; Timber Structures–Structural Timber and Glue-Laminated Timber Determination of Some Physical and Mechanical Properties. British Standard: London, UK, 2012.
29. Fink, G.; Kohler, J.; Brandner, R. Application of European design principles to cross laminated timber. *Eng. Struct.* **2018**, *171*, 934–943. [CrossRef]
30. Robert McNeel & Associates. *Rhinoceros 3D, Version 6.0*; Robert McNeel & Associates: Seattle, WA, USA, 2018. Available online: https://www.rhino3d.com/ (accessed on 20 March 2021).
31. CUSP Buidling Solution 2021; Austalia. Available online: https://cusp.com.au/products/ (accessed on 13 July 2021).
32. *BS EN 16351*; Timber Structures—Cross-Laminated Timber—Requirements. British Standard: London, UK, 2015.
33. Nero, R.; Christopher, P.; Ngo, T. Investigation of rolling shear properties of cross-laminated timber (CLT) and comparison of experimental approaches. *Constr. Build. Mater.* **2022**, *316*, 125897. [CrossRef]