Bond quality of cross-laminated timber from Irish Sitka spruce

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ABSTRACT:
The potential use of Irish-grown Sitka spruce for cross-laminated timber (CLT) manufacture is investigated as this would present new opportunities and novel products for Irish timber in the home and export markets. CLT is a prefabricated multi-layer engineered wood product made of at least three orthogonally bonded layers of timber. In order to increase rigidity and stability, successive layers of boards are placed cross-wise to form a solid timber panel. Load-bearing CLT wall and floor panels are easily assembled on site to form multi-storey buildings. This improves construction and project delivery time, reduces costs, and maximises efficiency on all levels.
The paper addresses the quality of the interface bond between the laminations making up the panels, which is of fundamental importance to the load bearing capacity. Therefore, shear tests were carried out on nine test bars of three glue lines each. Moreover, delamination tests were performed on samples subjected to accelerated aging, in order to assess the durability of bonds subjected to severe environmental conditions. In addition, this paper gives an indication on thickness tolerances of planed Irish Sitka spruce lamellas, which is likely to be a critical factor for bonding quality and adhesive selection. The test results of bond quality presented in this study were within requirements of prEN 16351:2013.

KEY WORDS: Sitka spruce, timber bonding, Cross-laminated timber

1 INTRODUCTION

More and more often construction materials are expected to comply with requirements reaching far beyond a general utility market. New high-performance materials are required not only to be more durable and exhibit a longer life time, even under severe environmental conditions but having consumed less energy during their life cycle. When compared with ordinary materials, they have to be more ecologically friendly and follow sustainability trends. One promising product satisfying such criteria is Cross-Laminated Timber (CLT).

CLT is a prefabricated multi-layer engineered panel wood product manufactured by gluing at least three layers of parallel boards. The wood grains of each layer are orientated perpendicular to wood grains of layers with which it is in contact. The number of laminates in CLT is odd, therefore face layers are parallel to each other. The advantages of this specific orientation between the laminates in regard to the load displacement and failure behaviour of such composite include increase in bearing capacity against in-plane and out-of-plane stresses, rigidity and stability [1-5]. The natural variations in timber strength, such as knots, are reduced in CLT in comparison with construction timber. Furthermore it is reported that cross-lamination of the boards reduces the degree of anisotropy in properties in the plane of the panel [6-9]. Moreover, load-bearing CLT wall and floor panels are easily assembled on site to form multi-storey buildings. This improves construction and project delivery time, reduces costs, and maximises efficiency on all levels [5, 10-13].

In order to investigate the suitability and to support the commercialisation of Irish-grown Sitka spruce for the manufacture of CLT panels, the development of necessary engineering data is required. The quality of the interface bond between the laminations making up the panels is of fundamental importance to the load bearing capacity. As a part of the testing programme of the project 'Innovation in Irish Timber Usage', shear tests were carried out on Sitka spruce bars with edge bonds in order to investigate their shear performance. Shear tests of glue lines are required in the course of factory production control in CLT plants. In most of the standards, the method of applying shear stress to the glue line is only given by a schematic diagram [14, 15]. The shear test tool used in the present study was manufactured in accordance with Annex D of prEN 16351:2013 Timber structures – Cross laminated timber – Requirements [16] that is based on EN 392 [17] and dimensions proposed by Steiger et al. [14, 15]. Moreover, delamination tests were performed on samples subjected to pressure soak-drying cycles, in order to assess the durability of bonds subjected to severe environmental conditions.

2 MATERIALS AND METHODS

The investigation of the quality of the bonded interface involved thickness tolerance testing of the boards, shear tests of the edge bonds and delamination testing.

2.1 Materials

In order to ensure a uniform moisture content in the specimens during the testing, boards of Irish Sitka spruce were stored in conditioning chamber (65±5% R.H., 20±2°C) for 3 months before specimen preparation. Subsequently, all sides of the boards were planed by a specialised company to cross-sectional dimensions of 96 mm by 30 mm.

A tight tolerance on the lamination thickness is required for the production of CLT due to the thin bond lines used. Because of this, thickness measurements were taken on the boards immediately after planing to determine whether the required tolerance of 0.1 mm is achieved. Thickness measurements were taken at 0.3 m, 0.6 m and 0.9 m from one end of the board. Two measurements were taken at each location, giving a total of 6 measurements per board. The maximum and minimum thickness values for each board are reported in Table 1, together with the deviation from the nominal value of 30 mm (green shadings for deviation ≤ 0.10 mm and light green for 0.11 mm & 0.12 mm). Only one sample failed to meet the required tolerance (board 5; red shading) and this board was excluded when the test specimens were manufactured.

Table 1. Thickness deviation results.

Board ID	Min value [mm]	Max value [mm]	30 – Min [mm]	Max – 30 [mm]
1	30.03	30.12	-0.03	0.12
2	29.93	30.12	0.07	0.12
3	29.88	30.02	0.12	0.02
4	29.99	30.11	0.01	0.11
5	29.75	30.02	0.25	0.02
6	29.97	30.10	0.03	0.10
7	29.97	30.08	0.03	0.08
8	29.99	30.09	0.01	0.09
9	29.98	30.11	0.02	0.11
10	29.88	30.07	0.12	0.07

For the purpose of specimens manufacture for shear tests, boards were cut to lengths of 300 mm. Two blocks comprising of 4 edge bonded 300 mm long boards were prepared. A single-component polyurethane adhesive, formulated for the manufacture of engineered wood products (PURBOND HB S309), was used to bond the edges of the shear test specimens. The 0.1 mm adhesive layer was applied on one surface of each glue line and 1 MPa pressure was applied by compressive testing machine for 120 minutes. Figure 1 shows the pressing process of shear tests samples.

Figure 1. Pressing of the shear test specimens

After reconditioning (65±5% R.H., 20±2°C), 9 test bars were cut from the blocks. Each of the test bars comprised three glue lines. The dimensions of these tests specimens were in accordance with prEN 16351:2013 [16] and were: 30 mm thick, 384 mm (4 glued pieces of 96 mm) long and 50 mm wide, see Figure 2.

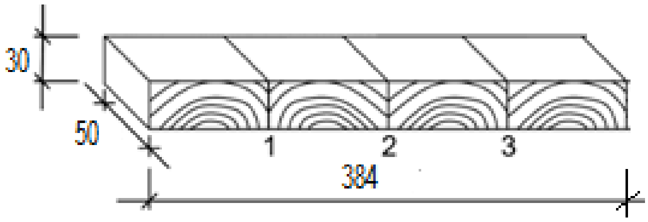

Figure 2. Shear test specimen dimensions

In order to prepare specimens for the delamination tests, a sample CLT panel of 90 mm (3 layers of 30 mm) thickness, 600 mm length and 192 mm width was manufactured. The same adhesive, thickness of adhesive layer was applied as for the shear tests samples. The pressure of 0.8 MPa was applied by compressive testing machine for 120 minutes. After reconditioning, specimens for the delamination tests of glue lines between layers were cut from this panel. Tests were carried out on 10 specimens of 105 mm by 96 mm by 90 mm, as shown in Figure 3.

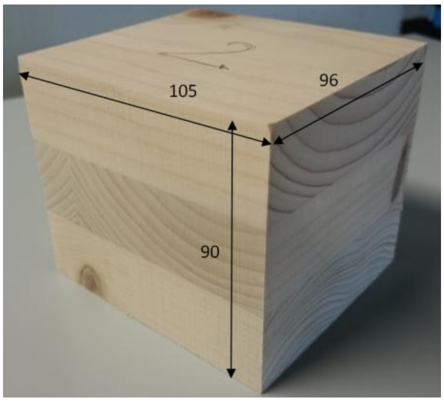

Figure 3. CLT delamination test specimen

2.2 Experimental techniques

The shear tests were carried out by applying a compression force using the shearing tool, which is illustrated in Figure 4. The cylindrical bearing was able to self-align so that the test piece could load at the end-grain with a stress field uniform in the width direction. A compressive testing machine was used to apply a compressive force to the shearing tool, as seen in Figure 5.

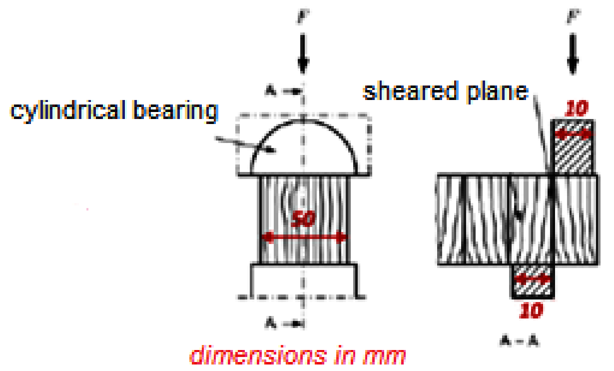

Figure 4. Shearing tool with a test bar inserted (adapted from [16, 17])

The test programme and procedure were in accordance with Annex D of prEN 16351:2013 Timber structures – Cross laminated timber – Requirements [16] that is based on EN 392 [17]. Loading was applied under displacement control at a rate of 3 mm/min, ensuring failure after no less than 20 s, which is in accordance with prEN 16351:2013 [16] and studies by Steiger et al. [14, 15]. The laboratory temperature and relative humidity were recorded as 17.9 ˚C and 63%, respectively. Just after the shearing tests, four samples 50 mm long from each test bar (central parts between glue lines or glue line and end) were cut and weighted in order to determine the density.

Figure 5. Test bar during testing in shearing tool

Test pieces for the glue line delamination tests were placed in the pressure vessel, as shown in Figure 6, and submerged in water at a temperature of about 15 °C. Then a vacuum of about 80 kPa was drawn and held for 30 min. Subsequently, the vacuum was released and pressure of about 550 kPa was applied for 2 h. Later, the test pieces were dried for a period of approximately 15 h in a circulating oven at a temperature of 70±5 °C. After removal from the oven, the delaminated length for each of the two glue lines was measured around the perimeter of the specimen. The maximum delamination length, $l_{max,delam}$ is the greater of these two values and the total delamination length, $l_{tot,glueline}$ is the sum of these two values. The two glue lines were then split using a wedge and hammer, and the wood failure percentage was estimated visually. The lower of the wood failure percentages from the two glue lines, FF_{min} was recorded.

The test programme and procedure were in accordance with Annex C of prEN 16351:2013 [16].

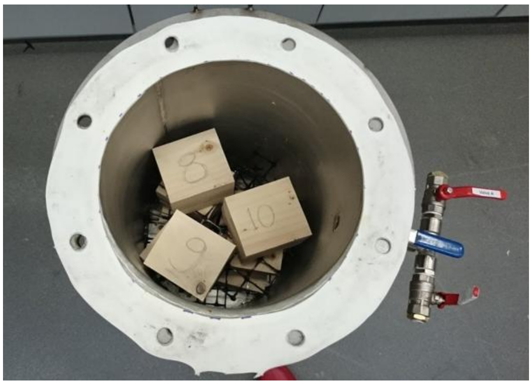

Figure 6. Delamination test samples in pressure vessel

3 RESULTS AND DISCUSSION

3.1 Shear strength

The shear strength was determined for every of 3 glue lines (a, b, c) from nine test bars and the results are given in Table 2. The shear strength was calculated in accordance with prEN 16351:2013 [16] as

$$f_v = k\frac{F_u}{A}$$

where:

F_u is the ultimate load (in N),
A is the sheared area (in mm^2),
k is a modification factor: k = 078 + 0.0044t,
t is thickness (in mm).

Table 2 presents the wood failure percentage of a split glue area that is the ratio of the area with wood failures and the glued area before splitting. Ultimate loads of each test and the determined average densities of two specimens from both sides of glue line for each glue line are also given in the Table 2.

The wood percentage failures were above 80% with exception of 75% for 7a. Wood failure percentages results for PUR type adhesives were generally very high and exhibited a small variation, which corresponds to results obtained by Steiger et al. [14, 15]. It is likely that low percentage in glueline 7a resulted from the presence of a knot on one of the sheared faces that increased the wood strength in this area. Figure 7 shows the glue line 7a after testing in comparison to glue line 8c with 100% wood failure.

The characteristic shear strength, $f_{v,k}$ for all tested glue lines was 7.24 N/mm^2, and mean shear strength was 8.11 N/mm^2 with standard deviation of 0.47 N/mm^2. These results were within the minimum requirement of 3.5 N/mm^2 for characteristic shear strength in accordance with prEN 16351 [16]. These results are also consistent with the findings of Raftery et al. [18] for the shear strength of Sitka spruce specimens bonded using a single component PU adhesive and tested in accordance with ISO 6238. Since the shear strength for each single glue line was above the threshold value of 2 N/mm^2 there is no condition to be satisfied in relation to the wood failure percentage [16]. for glue line a in sample 9, the requirement of wood failure percentage of 100% for each tested glue line with shear strength below 2 N/mm^2, in accordance with prEN16351 [16], was satisfied. However, considering the fact that the mechanical performance of CLT is largely determined by rolling shear and there is lack of available research on this property for Sitka spruce, the rolling shear strength of Sitka spruce should be comprehensively researched and established.

Table 2. Shear strength and wood percentage failure

Specimen ID		Ultimate load [kN]	Wood percentage failure [%]	Shear strength [N//mm^2]	Density [kg/m^3]
	a	13.64	100	8.29	412.87
	b	13.63	100	8.29	402.13
1	c	12.9	100	7.84	391.29
	a	14.01	100	8.52	401.16
	b	14.12	80	8.58	420.19
2	c	13.21	95	8.03	420.73
	a	13.57	100	8.25	450.91
	b	12.84	90	7.81	408.90
3	c	13.9	100	8.45	412.35
	a	13.52	100	8.22	402.16
	b	13.63	100	8.29	399.43
4	c	13.31	100	8.09	407.93
	a	13.91	100	8.46	407.82
	b	12.91	90	7.85	396.83
5	c	13.38	95	8.14	404.47
	a	13.83	100	8.41	407.89
	b	14.37	100	8.74	406.25
6	c	12.45	90	7.57	416.52
	a	11.75	75	7.14	442.03
	b	14.19	100	8.63	436.33
7	c	13.92	100	8.46	452.14
	a	13.85	90	8.42	458.23
	b	14.06	95	8.55	440.33
8	c	12.39	100	7.53	452.93
	a	11.31	100	6.88	424.25
	b	13.48	100	8.20	438.13
9	c	12.28	100	7.47	459.05
5-percentile Shear strength, $f_{v,k}$:				7.24	
Mean Shear strength:				8.11	
Standard deviation:				0.47	

Figure 7. Glue line 7a (left, 75% wood failure) and 8c (right, 100% wood failure) after test

The maximum delamination $Delam_{max}$ of a single glue line in each test piece was calculated from following formula:

$$\mathrm{Delam_{max}} = 100\,\frac{l_{max,delam}}{l_{glueline}}\ [\%]$$

where:

$l_{max,delam}$ is the maximum delamination length (in mm),
$l_{glueline}$ is the perimeter of one glue line in a delamination specimen (in mm).

The values of total delamination of each test piece and maximum delamination of a single line in each test piece are shown in Table 4. The delamination requirement in prEN16351 [16] can be satisfied in one of two ways:

(1) $\mathrm{Delam_{tot}} \leq 10\%$ and $\mathrm{Delam_{max}} \leq 40\%$ for all samples or
(2) If condition (1) is not satisfied, the wood failure percentage for each split glued area, FF, must be ≥ 50% and for the sum of the two split areas must be ≥70% .

None of the specimens passed Condition (1) but all tested specimens fulfilled Condition (2). The delamination occurred only in one of two glue lines for every tested specimen and the wood failure percentage for this glueline is reported in Table 3. As the FF value for the second glueline is 100% the requirement of the minimum wood failure percentage of the sum of all split glued areas ≥ 70% was also satisfied.

Table 3. Total and maximum delamination, and wood percentage failure

Specimen ID	$\mathrm{Delam_{tot}}$ [%]	$\mathrm{Delam_{max}}$ [%]	$\mathrm{FF_{min}}$ [%]
1	16.8	33.7	80%
2	17.6	35.2	75%
3	27.3	54.2	60%
4	16.0	32.0	85%
5	19.5	38.9	70%
6	21.7	43.7	65%
7	17.0	34.0	80%
8	23.1	46.2	65%
9	19.8	39.6	70%
10	28.2	56.3	60%

Although delamination results vary significantly between the test pieces, it is very likely that the mechanism resulted in the delamination of glue lines was the same for all specimens. In all cases delamination occurred in one glue line along one side as presented in Figure 8. Since the vacuum-pressure soak cycle resulted in swelling, which was much higher in the tangential and radial directions than the longitudinal direction for the timber, it induced significant internal shear stresses between the bonded surfaces.

Furthermore, since there was no edge bonding of the boards in each CLT layer, the lowest bonding area was in the narrowest timber elements, which were part of middle layers in every specimen. Since these elements were placed in one side of test piece, delamination occurred at their surfaces, which may be observed in Figure 9.

Moreover, widths of the narrowest timber elements in each test piece determined the depth of delamination.

Figure 8. Delamination of specimen 6. after vacuum-pressure cycle

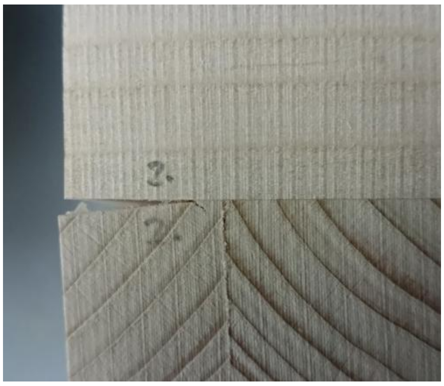

Figure 9. Delamination of specimen 2. after vacuum-pressure cycle

4 CONCLUSIONS

Preliminary investigations presented in this paper can lead to the following conclusions:

- it was confirmed that wood percentage failure results for PUR type adhesives are very high with small variations,
- the results presented for the shear strength and delamination were within requirements of prEN 16351:2013,
- the widths of the narrowest timber elements in CLT test piece determine the depth of delamination.

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REFERENCES

[1] Schickhofer G. (1994). *Starrer und nachgiebiger Verbund bei geschichteten, flächenhaften Holzstrukturen*, PhD Thesis, Institute of Steel, Timber and Shell Structures, Graz University of Technology.

[2] Salmén L. (2004). *Micromechanical understanding of the cell-wall structure*, C. R. Biologies, 327:873-880.

[3] Wathén R. (2006). *Studies on fiber strength and its effect on paper properties*, PhD Thesis, KLC communications, No. 11, University of Technology, Helsinki, Finland, ISSN 1457-6252, p. 97.

[4] Brandner R. (2012). *Stochastic System Actions and Effects in Engineered Timber Products and Structures*, PhD Thesis, Institute of Timber Engineering and Wood Technology, Graz University of Technology, p. 467.

[5] Brandner R. (2013). *Production and Technology of Cross Laminated Timber (CLT): A state-of-the-art Report*, ECOST-MEETING-FP1004-210513-028873, ISBN 1 85790 181 9, p. 3-36.

[6] Jobstl, R.A., Bogensperger, T., and Schickhofer, G. (2008*) In-plane shear strength of Cross Laminated Timber*, CIB-W18/41-21-3, St. Andrews.

[7] Mestek, P., Kreuzinger, H., and Winter, S. (2008). *Design of Cross Laminated Timber (CLT)*, WCTE 2008 - 10th World Conference on Timber Engineering, Miyazaki, Japan.

[8] Vessby, J., Enquist, B., Petersson, H., and Alsmarker, T. (2009). *Experimental study of cross-laminated timber wall panels*, European Journal of Wood Products, 67: 211-218.

[9] Fortune, A.L., Quenneville, P. (2010). *Feasibility study of New Zealan radiata pine crosslam*, in S. Setunge (ed.) Incorporating sustainable practise in mechanics and structures of materials, CRC Press.

[10] Leonardo da Vinci Pilot Project. (2008). Handbook 1. Timber structures, Educational Materials for Designing and Testing Timber Structures – TEMTIS.

[11] Crespell, P., and Gagnon, S., (2010) Cross Laminated Timber: a Premier, FPInnovations.

[12] Rimetz, B. (2011). Future of Wood Update / X Marks the Opportunity, ProSales, http://www.prosalesmagazine.com/products/lumber/x-marks-the-opportunity_o.

[13] Yeh, B., Gagnon, S., Williamson, T., Pirvu, C., Lum, C., and Kretschmann, D. (2012). *The North American product standard for cross-laminated timber*, Wood Design Focus, 22(2):13-21.

[14] Steiger, R. and Gehri, E. (2010*). Quality control of glulam: Improved method for shear testing of glue lines* 'The Future of Quality Control for Wood & Wood Products' The Final Conference of COST Action E53, Edinburgh.

[15] Steiger, R., Gehri, E., and Richter K. (2010). *Quality control of glulam: shear testing of bondlines*, Eur. J. Wood Prod. 68: 243–256.

[16] prEN 16351:2013 Timber structures – Cross laminated timber – Requirements, CEN.

[17] EN 392:1995 Glued Laminated Timber – Shear Test of glue lines, CEN.

[18] Raftery, G., Harte, A., Rodd, P. (2008). *Qualification of wood adhesives for structural softwood glulam with large juvenile wood contentJ*. J. of Institute of Wood Science, 18(1): 24-34.