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Durability of adhesive bonds in cross-laminated timber (CLT) panels manufactured using 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. Furthermore, in order to assess the adhesive performance, which is an essential parameter in terms of the production process, three different values of pressure of 0.6 N/mm^2, 0.8 N/mm^2 and 1.0 N/mm^2 were used for specimens manufacturing. In total, 240 shear tests were carried out on glue lines and on reference solid wood specimens. Moreover, delamination tests were performed on samples subjected to accelerated aging, in order to assess the durability of bonds subjected to severe environmental conditions. The test results of bond quality presented in this study were within requirements of prEN 16351:2013. Even the lowest pressure of 0.6 N/mm^2 applied during manufacturing of the specimens is sufficient for Irish Sitka spruce in terms of the shear strength requirements. However, factors influencing this quality include: the adhesive type, the spread rate, the clamping pressure, and most importantly rolling shear. Therefore, in order to assess the potential use of Irish-grown Sitka spruce for CLT, all these factors need to be addressed in the ongoing project.

Keywords: Cross-laminated timber (CLT), Sitka spruce, Bonding, Delamination, Shear

Introduction

The construction industry like any other area of economic and social life undergoes continuous alterations and improvements in order to successfully comply with the requirements of sustainable development. Consumers demand materials with enhanced mechanical properties, more durable, less labour and service intensive at a competitive price. To meet these expectations numerous new engineered wood products have been developed over the last couple of decades. One of promising products satisfying such criteria is Cross-laminated timber (CLT).

CLT is a prefabricated wood product manufactured using at least three layers of parallel boards. The wood grains of each layer are orientated perpendicular to the wood grains of the layers with which it is in contact. These layers are bonded by gluing their surfaces together with an adhesive under a pressure for a period of time. The adhesives used for CLT production include: phenoplast- and aminoplast-adhesives, one-component polyurethane adhesives (1K-PUR) and emulsion-polymer-isocyanate adhesives (EPI). 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 load-bearing capacity against in-plane and out-of-plane stresses, rigidity and stability (Jobstl et al. 2008, Brandner 2012, 2013). The natural variations in timber strength, due to defects such as knots, are reduced in CLT in comparison with construction timber. Furthermore, it was reported that cross-lamination of the boards reduces the degree of anisotropy in properties in the plane of the panel (Jobstl et al. 2008, Mestek et al. 2008, Vessby et al. 2009, Fortune and Quenneville 2010). 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 (Brandner 2013, Leonardo da Vinci Pilot Project 2008, Crespell and Gagnon 2010, Rimetz 2011, Yeh et al. 2012).

In order to investigate the suitability and 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, a crucial property for every construction material. Shear tests of glue lines are required in the course of factory production control in CLT plants. Additionally, in order to assess the durability of bonds that are often subjected to severe environmental conditions, delamination tests on samples subjected to pressure soak-drying cycles are performed. As a part of the testing programme of the project 'Innovation in Irish Timber Usage', these tests were carried out on samples manufactured using Irish Sitka spruce in order to investigate adhesive bonds' shear performance and durability.

Materials and Methods

Materials

In order to ensure a uniform moisture content in the specimens during the testing, boards of Irish Sitka spruce were stored in a 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 94 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 was achieved. The boards that failed to meet the required tolerance were excluded when the test specimens were manufactured.
For the purpose of specimen manufacture for shear tests, boards were cut to lengths of 300 mm. Two blocks comprising 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. Three different values of pressure, namely 0.6 N/mm^2, 0.8 N/mm^2 and 1.0 N/mm^2, were applied by a compressive testing machine for 120 minutes.
After reconditioning (65±5% R.H., 20±2°C), 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 and were: 30 mm thick, 376 mm (4 glued pieces of 94 mm) long and 50 mm wide, as seen in Figure 1. In addition, solid wood specimens, without glue line, of the same cross-sectional dimensions were prepared.

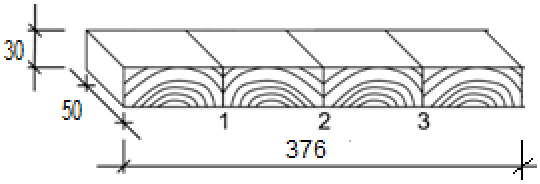


Figure 1. Shear test specimen dimensions

Table 1 presents the numbers of lines tested for different bonding pressures in end-grain and perpendicular to grain directions. The number of specimens for 1.0 N/mm^2 loaded perpendicular to the grain is very small, because this study is still ongoing.

Table 1. Numbers of shear tests

Bonding pressure	***0.6 N/mm^2***	***0.8 N/mm^2***	***1.0 N/mm^2***	***Solid wood (unglued)***
End-grain	36	36	27	36
Perpendicular to grain	36	24	9	36

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 as for the shear tests samples was used and a pressure of 0.8 N/mm^2 was applied. 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.

Experimental techniques
The shear tests were carried out by applying a compressive force using a shearing tool adapted from prEN 16351:2013. The cylindrical bearing was able to self-align so that the test piece could load at the end-grain and perpendicular to 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 2.
The prEN 16351:2013 standard requires loading tested specimens at the end-grain. However, since in CLT panels wood grains of each layer are orientated perpendicular to wood grains of layers with which it is in contact, the shear stresses occur in different planes of boards comprising CLT panels. Because of this, the additional tests were carried out for the specimens loaded perpendicular to grain, see Figure 2 (b).
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 and studies by Steiger et al. (2010). 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.

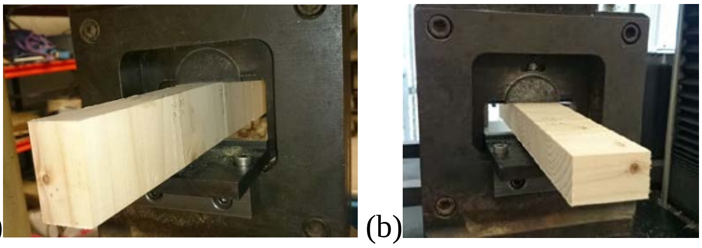
(a)  (b)

Figure 2. Test bar during testing in shearing tool loading end-grain (a) and perpendicular to grain (b)

Test pieces for the glue line delamination tests were placed in a pressure vessel 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.

Results and Discussion

Shear

The shear strength was determined for each of 3 glue lines from each test bar and the results are given in Figure 3, which presents the mean, 5-percentile and standard deviations of shear strengths for samples manufactured with different pressures and for solid wood specimens.

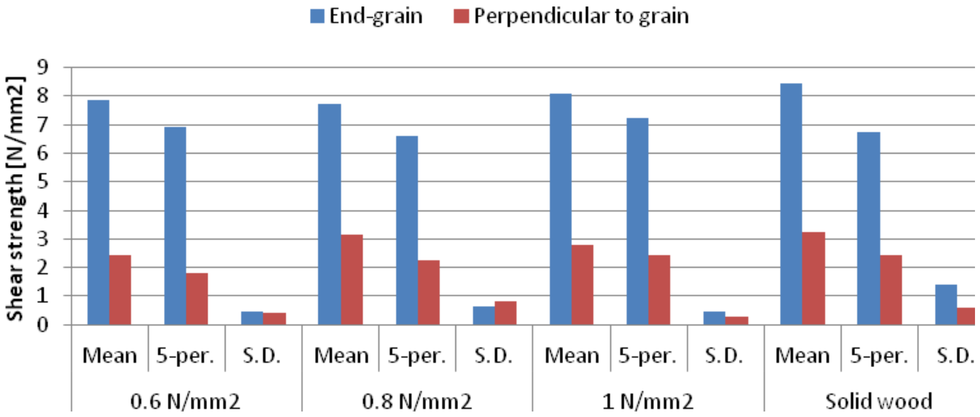


Figure 3. Shear strength values

The characteristic shear strengths, $f_{v,k}$, were 6.92 N/mm^2, 6.61 N/mm^2 and 7.24 N/mm^2 for glue lines loaded at end-grain and manufactured with pressures of 0.6 N/mm^2, 0.8 N/mm^2, 1 N/mm^2, respectively. These results were well in excess of the minimum requirement of 3.5 N/mm^2 for characteristic shear strength in accordance with prEN 16351:2013. Furthermore, 6.74 N/mm^2 was recorded characteristic shear strength, for solid wood specimens. This value is even lower than for specimens bonded at 0.6 N/mm^2 and 1 N/mm^2 pressures. These results give an indication that the lowest pressure of 0.6 N/mm^2 applied during manufacturing of the specimens is sufficient for Irish Sitka spruce in terms of the prEN 16351:2013 shear strength requirements.

The characteristic shear strengths were 1.81 N/mm^2, 2.24 N/mm^2, 2.44 N/mm^2, and 2.42 N/mm^2 for glue lines loaded perpendicular to grain, bonded at pressures of 0.6 N/mm^2, 0.8 N/mm^2, 1 N/mm^2, and solid wood, respectively. The characteristic shear strengths for glue lines loaded perpendicular to grain were lower by 74%, 66% and 66% in comparison to values for corresponding lines manufactured with different pressures loaded at end-grain. These values were consistent with result for solid wood specimens, for which a reduction of characteristic shear strengths of 64% between specimens loaded perpendicular to grain compared to those loaded at the end-grain.

The Student's *t*-test statistical comparison for the specimens loaded on the end-grain showed that the characteristic shear strength of specimens bonded at pressures of 0.6 N/mm^2 and 0.8 N/mm^2 were significantly different to the solid wood shear strength values. However, for the specimens loaded perpendicular to grain, the 0.6 N/mm^2 and 1.0 N/mm^2 bonded specimens were found to be significantly different to the equivalent solid wood strength values. It should be noted, however, that the number of test results for the 1.0 N/mm^2 pressure case is very small. Nevertheless, 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.

A mean density of 436.41 kg/m^3 with standard deviation of 47.79 kg/m^3 was obtained for all tested samples. The wood percentage failures (split glue area that is the ratio of the area with wood failures and the glued area before splitting) for 96% of all tested glue lines in both grain directions were above or equal 80%, and for 69% of the samples the wood percentage failures were 100%. These recordings have confirmed that wood failure percentages values for PUR type adhesives are generally very high and exhibit a small variation, which corresponds to results obtained by Steiger et al. (2010). The lowest wood failure percentage was 60% and occurred in a bond line manufactured with 0.8 N/mm^2 pressure and tested perpendicular to grain, see Figure 4 (a). It is likely that this low value was due to the presence of a large knot on one of the sheared faces. Figure 4 shows this glue line after testing in comparison to glue lines with 100% wood failure loaded perpendicular to grain (b) and at end-grain (c).


(a) (b) (c)

Figure 4. Glue lines with 60% wood failure loaded perpendicular to grain (a), 100% wood failure loaded perpendicular to grain (b), and 100% wood failure loaded at end-grain (c)

Delamination of glue lines

The total delamination $Delam_{tot}$ of each test piece was calculated from following Equation (1):

$$\mathrm{Delam}_{tot} = 100 \frac{l_{tot,delam}}{l_{tot,glueline}} \, [\%] \qquad \text{Equation (1)}$$

where:
$l_{tot,delam}$ is the total delamination length (in mm),
$l_{tot,glueline}$ is the sum of the perimeters of all glue lines in a delamination specimen (in mm).
The maximum delamination $Delam_{max}$ of a single glue line in each test piece was calculated from following Equation (2):

$$\mathrm{Delam}_{max} = 100 \frac{l_{max,delam}}{l_{glueline}} \, [\%] \qquad \text{Equation (2)}$$

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, $Delam_{tot}$ of each test piece and maximum delamination, $Delam_{max}$ of a single line in each test piece are shown in Table 2.
Since the delamination values exceeded the prEN 16351:2013 criteria of $\mathrm{Delam}_{tot} \leq 10\%$ and $\mathrm{Delam}_{max} \leq 40\%$ for all samples, the wood failure percentage of each split glued area was determined. All tested samples fulfilled the criteria of $FF_{min} \geq 50\%$, as presented in Table 2. Moreover, since the delamination occurred only in one of two glue lines for every tested specimen, the requirement of the minimum wood failure percentage of the sum of all split glued areas ≥ 70% was also satisfied.

Table 2. Total and maximum delamination, and wood percentage failure

Specimen ID	*$Delam_{tot}$ [%]*	*$Delam_{max}$ [%]*	*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 resulting in the delamination of glue lines was the same for all specimens. In all cases, delamination occurred in one glue line on one side. 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 to volume ratio was in the narrowest timber elements. Since these elements were placed in one side of the test piece, delamination occurred at their surfaces, which may be observed in Figure 5.

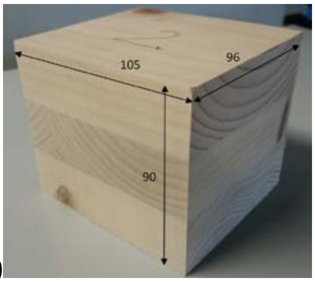
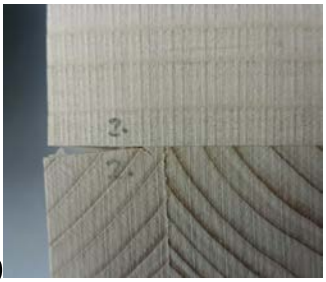
(a)  (b) 

Figure 5. Specimen for delamination test before (a) and after vacuum-pressure cycle (b)

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

Conclusions

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

- the lowest pressure of 0.6 N/mm^2 applied during manufacturing of the specimens is sufficient for Irish Sitka spruce in terms of the prEN 16351:2013 shear strength requirements,
- 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 the required limits given in prEN 16351:2013,

- the widths of the narrowest timber elements in CLT test piece determine the size of delamination.

Acknowledgments

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