Shear Strength and Durability Testing of Adhesive Bonds in Cross-Laminated Timber

Shear strength and durability testing of adhesive bonds in cross-laminated timber

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Abstract

The paper addresses the quality of the interface and edge bonded joints in layers of cross-laminated timber (CLT) panels. The shear performance was studied to assess the suitability of two different adhesives, Polyurethane (PUR) and Phenol-Resorcinol-Formaldehyde (PRF), and to determine the optimum clamping pressure. Since there is no established testing procedure to determine the shear strength of the surface bonds between layers in a CLT panel, block shear tests of specimens in two different configurations were carried out, and further shear tests of edge bonded specimen in two configurations were performed. Delamination tests were performed on samples which were subjected to accelerated aging to assess the durability of bonds in severe environmental conditions. Both tested adhesives produced boards with shear strength values within the edge bonding requirements of prEN 16351 for all manufacturing pressures. While the PUR specimens had higher shear strength values, the PRF specimens demonstrated superior durability characteristics in the delamination tests. It seems that the test protocol introduced in this study for crosslam bonded specimens, cut from a CLT panel, and placed in the shearing tool horizontally, accurately reflects the shearing strength of glue lines in CLT.

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Keywords

CLT, engineered wood, durability, adhesives for wood, joint design, delamination

1. Introduction

1.1 CLT concept

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, even under severe environmental conditions, but having consumed less energy during their life cycle. When compared with conventional materials, they have to be more ecologically friendly and follow sustainability trends. One promising product, satisfying the criteria of sustainability, is CLT.

CLT is a prefabricated multi-layer engineered panel wood product, with the grain direction of consecutive layers orthogonally orientated, bonded by gluing their surfaces together with an adhesive under pressure for a period of time. This specific orientation results in increased in-plane and out-of-plane strength, rigidity and stability. The degree of anisotropy in properties and the influence of natural variations, such as knots, are reduced in comparison with construction timber [1-6]. Load-bearing CLT wall and floor panels are easily assembled on site to form multi-storey buildings, improving construction and project delivery time, reducing costs, and maximising efficiency on all levels [2, 7-10].

1.2 Testing of adhesive bond quality

Different standard testing procedures for determining the quality of the interface bond between the laminations have been established, which are based on determination of local shear strength and wood failure percentage, according to the standards such as EN 302 [11], EN 392 [12], ASTM D 905 [13]. As pointed out by Steiger et al. [14, 15], only general principles of the methods of applying shear stress to the bond line are presented in the relevant standards. In accordance with EN 302 [11], the shear strength of adhesive bonds is determined by applying a longitudinal tensile force to a single lap joint with close contact or thick glue lines between two rectangular wooden elements. In EN 392 [12], a cylindrical bearing is specified that is able to self-align so that the test piece can be loaded at the end-grain with a stress field uniform in the width direction. A similar shearing tool is proposed by ASTM 905 [13], however, the difference in comparison with EN 392 [12] is that the two blocks comprising the specimen are bonded in a staggered (lapped) configuration. In all these methods, pure shear stress cannot be obtained, but the resulting stress in the bond line is a combination of shear and normal stresses [14-17]. When the normal stresses are acting as tensile stresses perpendicular to the bond line, the recorded shear strength values range considerably below the pure shear stress level, while compression stresses perpendicular to the grain lead to an overestimation of the shear strength of the bond line. In order to limit this effect, Steiger et al. [14, 15] developed a prototype of a modified shear test device, which ensures a clearly defined state of shear loading of the specimens.

Because of these limitations in the methodologies used for assessing adhesive bonds performance, it is generally accepted that no single test procedure can provide all of the information to definitively measure bonding quality [18]. Since it is believed that many factors influence the results including the strength of the wood, the specimen geometry, the shear tool design, and the rate of loading, wood failure percentage is often recorded in order to assess the quality of adhesive bond [19]. It provides information whether the superior strength is in the timber or the bond, but lacks information on the failure behaviour [20].

In order to compare and assess the suitability of different testing protocols for adhesive bonds, Serrano [17] modelled the adhesive layers in the specimens in accordance with different codes, including: ASTM-D 905 [13] and EN-302 [11] using a nonlinear softening, fracture mechanics model. The results showed that the prediction of bond line strength is highly dependent on the specimen type used and the adhesive properties. On the other hand, Davalos et al. [21] found the block-shear tests of ASTM D 905 [13], as the most suitable for obtaining the average interface shear strengths when testing fibre-reinforced plastic (FRP)-wood bonds, where the combination of various parameters affects measurement. The stiffness imbalance that arises from the bonding of dissimilar materials was noted as being an important issue in the shear stress distribution in other studies [22, 23]. Furthermore, when two materials of different stiffness are bonded together, the shear stress and transverse normal stress in the adhesive layer are responsible for the initiation of the failure of the adhesively bonding joints near the free ends of adhesively bonding region where the peak stresses occur [24].

In addition to the mechanical properties of adhesive, other factors influencing adhesive performance such as temperature, humidity or ageing of the bonds should be taken into consideration [25-27]. This was evidenced in an extensive study by Raftery et al. [28] on the hygrothermal compliance of a variety of wood-laminating adhesives when bonding FRP materials to wood. Raftery et al. [29] also showed that with specific adhesives, cost-effective thin bond lines have the capacity to resist severe hydrothermal stresses imposed at the FRP–wood interface. Lavisci et al. [30] examined delamination of thick joints after accelerated ageing cycles and concluded that the delamination test seemed to be effective in characterising the performance of the boned joint. Another factor that seemed to have significant effect on the performance of adhesively bonded timber joints is occurrence of defects. The empirical and numerical study of the influence of artificial defects on the capacity of adhesively bonded timber joints by Grunwald et. al [31] demonstrated that joints with a 50% defect area still achieved a capacity of 70% of that of defect-free joints.

1.3 CLT delamination testing

The provisional European Standard EN 16351:2013 [32] is the first European code strictly dedicated to CLT that sets out provisions regarding the performance characteristics of CLT for use in buildings and bridges. According to prEN 16351 [32], the resistance of edge bonding has to be controlled by means of block shear tests according to EN 392 [12]. For controlling the adhesion or the resistance against fractures in the bond line, specimens of defined geometry have to be exposed to a specific series of climatic conditions and afterwards the delamination of their bond lines has to be determined (more details in section 2.2).

In accordance with Canadian [33] and U.S. [34] CLT Handbooks, wood failure results from block shear specimens tested under vacuum-pressure-dry conditions can be used to assess the bond quality. It is considered that dry wood failures lacked consistency and should not be considered as a reasonable criterion in assessing the bond quality of CLT panels. Only the vacuum-pressure-dry wood failures showed consistency in assessing the bond quality of CLT panels [35]. In addition to the influence of timber moisture content and temperature, factors such as distortion and wane have a negative influence on bonding strength due to their effect on the bond line geometry. Therefore, in accordance to ANSI/APA PRG 320-2012 [36], an 'effective bonding area', defined as the proportion of the lamination wide face averaged over its width that is able to form a close bond upon application of pressure, of 80% is required.

In order to clarify the consequences of the interacting parameters bonding pressure and spreading rate on CLT production, a comprehensive research project was conducted [3, 37]. Two types of one-component polyurethane (1K-PUR) adhesives, three bonding pressures of (0.1, 0.3, 0.6) N/mm² and various spreading rate were investigated. Additionally, the effect of cyclic climatic variations (20 °C / 90 % RH and 30 °C / 40 % RH; numbers of cycles: 0, 10, 21, 25) on the properties of bonding was also analysed. The bonding properties were investigated by means of rolling shear tests on whole CLT elements in bending according to EN 408 [38], block (rolling) shear tests on the single glue line according to EN 392 [12], and delamination tests according to EN 391 [39]. The investigated bonding pressures were found to be sufficient to realise adequate bond qualities provided the thickness variations between boards of the same CLT layer was kept low. It was found that parameters like warp or twist of the board material showed nearly no or at least negligible effects on surface bonding. Further, a positive relationship between bonding pressure and shear strength was observed in cases where the applied spreading rate was lower than that recommended by the manufacturer or the deviations in thickness were too high.

1.4 Adhesives systems for CLT

Generally, adhesives are grouped according to their chemistry [25, 40]. However, Frihart [41] proposed to consider not only the chemical, but also the mechanical response of adhesives and therefore suggested to differentiate between two main groups: in-situ polymerised and pre-polymerised adhesives. The in-situ polymerised adhesives contain relatively rigid, highly crosslinked polymers such as urea-formaldehyde (UF), melamine formaldehyde (MF), melamine-urea-formaldehyde (MUF), phenol-formaldehyde (PF), phenol-resorcinol- formaldehyde (PRF), but also polymeric methylene-diphenyl-diisocyanate (pMDI), where as the second group includes flexible polymers such as polyurethane (PUR) and polyvinyl acetate (PVAc). These two groups differ significantly in their ability to distribute moisture induced stress in an adhesive bond resulting in different failure mechanisms.

The adhesive systems which are allowed for use in CLT production according to prEN 16351 [31], and the Canadian [33] and U.S. [34] CLT Handbooks are:

- phenoplast- and aminoplast-adhesives; these include adhesives primary MUF and PRF,
- one-component polyurethane adhesives (1K-PUR);
- emulsion-polymer-isocyanate adhesive (EPI).

Typical characteristics of these adhesives are presented in Table 1. It should be noted that while Table 1 gives recommended values for wood moisture content, application rate, applied pressure, and assembly and pressing times, in practice specific manufacturers' requirements must be followed.

PRF is a popular adhesive for structural use (commonly used for glulam manufacturing), which is the cheapest (per kg) among such adhesive systems. However, PRF requires a higher spreading rate than PUR (approx. 3 times) and EPI, and much longer pressing time than EPI and PUR. PRF is dark brown, which may be an issue in terms of aesthetic quality, and contains formaldehyde whereas EPI and PUR are light-coloured and formaldehyde-free. Due to the chemical reaction with water, PUR produces slight foaming during hardening. PRF, EPI and PUR are in principal suitable for bonding of finger joints as well as edge and surface bonding, however EPI, according with prEN 16351 [32], is not allowed for large finger joints.

1.5. Objectives of the present study

In order to address the quality of the interface bonds in CLT it has been intended to:

- assess the suitability of different adhesives and to determine the optimum clamping pressure;
- assess the durability of adhesive bonds;
- make recommendations on suitable testing protocol for adhesive bonds in CLT.

2. Materials and methods

In order to realize the objectives of this study, a research program consisting of shear and delamination tests was carried out. Further, for shear testing, specimens of two geometries were manufactured, one group of specimens, edge bonded in accordance with prEN 16351 [32], and another group, faced bonded, cut from manufactured CLT panels. Loadings during shear testing were applied in two different directions for each specimen group, as shown in Figure 1 (abbreviations for each specimen configuration are also presented).

Specimens for delamination tests were also cut from CLT panels. The delamination tests followed procedures outlined in prEN 16351 [32]. Two types of adhesives, PUR and PRF, using four different manufacturing pressures, were used for specimen preparation during the course of this study.

2.1 Materials

2.1.1 Timber

In order to ensure a uniform moisture content of 12% (measured by Handheld Moisture Meter GE Protimeter BLD5602 Timbermaster) in the specimens during the testing, boards of C16 Irish Sitka spruce (*Picea sitchensis*) 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.

2.1.2 Adhesives

A 1K-PUR adhesive (PURBOND HB S309, Purbond AG, Sempach, Switzerland) and a two-component PRF adhesive (Prefere 4050 M with hardener Prefere 5750, Dynea UK, Flintshire, UK, using a ratio of 1:1), formulated for the manufacture of engineered wood products systems, were used to bond the edges of the shear test specimens. The reasons for such selection are related to extremes in values of relevant factors between these two systems: application rate, pressing time and costs. In addition, their structural performance is considered to be superior to EPI.

2.2 Methodology

2.2.1 Specimen preparation

The adhesive systems were applied on one of the bonded surfaces at the rate of 160 g/m^2 for PUR, and on both surfaces at the rate of 400 g/m^2 (200 g/m^2 on each surface of glue line) for PRF, as recommended by the adhesive manufacturers. Four different values of pressure, namely 0.4 N/mm^2, 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 for the PUR-bonded specimens and for 16 hours the PRF-bonded specimens. Pressing time is a function of temperature and, as the ambient laboratory temperature was approximately 17 °C for the PRF-bonded specimens, the selected pressing time was to ensure compliance with the manufacturer's recommended minimum for cold bonding (15 h for 15°C) [42]. The manufacturers recommend applying pressure from 0.6 N/mm^2 to 1.0 N/mm^2 for softwoods, for both adhesives. These were addressed in this study and additionally samples prepared using lower pressure, 0.4 N/mm^2, were tested to assess this lower pressure potential usage that may facilitate CLT production. After reconditioning (65±5% R.H., 20±2°C), test specimens were cut to size.

The two sets of specimens, which were edge bonded, had bonded areas of dimensions 30 mm thick and 50 mm wide, in accordance with prEN 16351:2013 [32]. In addition, solid wood specimens, without glue lines, of the same cross-sectional dimensions were prepared.

In order to prepare specimens for the shear tests of crosslam bonded elements (specimens bonded orthogonally) and the delamination tests, sample CLT panels of 90 mm (3 layers of 30 mm) thickness were manufactured. Panels were face-bonded only; there were no edge bonds in these CLT panels. After reconditioning (for min. 2 weeks to 12% moisture content), specimens for the shear tests of crosslam bonded elements and for the delamination tests of glue lines between layers were cut from these panels. These specimens had cross-sectional dimensions of 30 mm by 50 mm as for edge bonded specimens. Figure 2 presents schemas of the shear tests specimens for end-grain (a) and perpendicular to grain loading directions (b) and shear test specimens for crosslam bonded elements vertical (c) and horizontal (d) loading directions.

Table 2 presents the numbers of shear test specimens for the different bonding pressures, adhesives and test configurations.

The delamination tests were carried out on 10 specimens of 100 mm by 100 mm by 90 mm for each adhesive type and manufacturing pressure. The number of specimens for shear and delamination tests is in accordance with recommendations of 'Factory production control for cross laminated timber products' from prEN 16351:2013 [32].

2.2.2 Shear testing

The shear tests were carried out by applying a compressive force using a shearing tool in accordance with EN 392 [12]. 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. The EN 392 [12] standard requires loading tested specimens at the end-grain. However, since in CLT panels the wood grain of each layer are orientated perpendicular to wood grains of layers with which it is in contact, the shear stresses occur in different planes. Because of this, tests were carried out with specimens loaded perpendicular to grain, and for the crosslam specimens. Loads were applied in the vertical and horizontal directions. 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 EN 392 [12] and studies by Steiger et al. [14, 15]. Just after the shearing tests, 50 mm long portions were cut from each specimen, and weighted in order to determine the density.

For the purpose of the shear testing analyses Student's t-test was carried out for comparison of shear strengths results for different manufacturing pressures. As a matter of good scientific practice, a significance level of 5% was chosen for a two-tailed test for two-sample unequal variance.

2.2.3 Delamination testing

The test programme and procedure were in accordance with Annex C of prEN 16351:2013 [32]. 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 lower of the wood fibres failure percentages from the two glue lines, FF_{min}, and the sum of the two split areas, FF_{tot}, were recorded.

3. Results

3.1 Shear tests

The shear strength f_v was determined for every tested glue line and was calculated in accordance with the following formula:

$$f_v = \frac{F_u}{A} \qquad \text{Equation (1)}$$

where:

F_u is the ultimate load (in N),

A is the sheared area (in mm^2).

Figure 3 presents the mean (M), 5-percentile (5%) and standard deviations (SD) of shear strengths for samples manufactured with different pressures and configurations, and for solid wood (SW) specimens.

Difference between test methods led to large differences in results. The values for end-grain loaded specimens on average at least 3 times higher than for other testing configurations. The differences between edge bonded specimens loaded perpendicular to grain and crosslam specimens were less pronounced. The 5-percentile shear strengths for glue lines loaded at end-grain were very consistent for PUR adhesive type, and were between 7.3 N/mm^2 (manufactured with pressure of 0.4, 0.8, 1.0 N/mm^2) and 7.6 N/mm^2 (manufactured with pressure of 0.6 N/mm^2). In addition, these results were in line with the result for solid wood specimens, which was 7.4 N/mm^2. For the equivalent specimens bonded using the PRF adhesive system, the 5-percentile shear strength values varied more and were between 6.4 N/mm^2 for 0.4 N/mm^2 and 8.4 N/mm^2 for 1.0 N/mm^2 manufacturing pressure. Standard deviation values were around 0.52 N/mm^2 for all edge bonded, end-grain loaded specimens, 0.36 N/mm^2 for perpendicular to grain loaded, 0.23 N/mm^2 for crosslam specimens, vertically placed, and 0.18 N/mm^2 for crosslam specimens, horizontally placed in shear block tool. A mean density of 427.12 kg/m^3 with standard deviation of 42.51 kg/m^3 was obtained for all tested samples.

3.2 Delamination of glue lines

The total delamination $Delam_{tot}$ of each test piece was calculated using Equation (2):

$$Delam_{tot} = 100\,\frac{l_{tot,delam}}{l_{tot,glueline}}\ [\%] \qquad \text{Equation (2)}$$

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 (3):

$$Delam_{max} = 100\,\frac{l_{max,delam}}{l_{glueline}}\ [\%] \qquad \text{Equation (3)}$$

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 delamination requirement in prEN16351 [31] can be satisfied in one of two ways:

- Condition (1): $Delam_{tot} \leq 10\%$ and $Delam_{max} \leq 40\%$ for all samples

or

- Condition (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% .

In Figure 4, median values are presented of the following results for specimens manufactured using different pressures: total and maximum delamination, and the lower of the wood failure percentages from the two glue lines and the sum of the two split areas. In addition, maximum values of $Delam_{tot}$ and $Delam_{max}$, and minimum of FF_{min} and FF_{tot} of all specimens for different manufacturing pressures are presented.

Delamination condition (1) of prEN 16351 [32] was not satisfied in any of the specimens, but Condition (2) was fulfilled for specimens manufactured using PUR adhesive with 0.8 N/mm^2 pressure and PRF system with 1.0 N/mm^2.

4. Discussion

4.1 Bonding strength

4.1.1 The effect of manufacturing pressure

The shear tests results give an indication that the lowest pressure of 0.4 N/mm^2 applied during manufacturing of the specimens is sufficient for Irish Sitka spruce in terms of the prEN 16351:2013 [31] shear strength requirements for both adhesive systems despite the manufacturers' minimum requirement of 0.6 N/mm^2. 5-percentile shear strength values for different test configurations manufactured with different pressures and adhesive systems PUR and PRF are compared in Figure 5.

The Student's t-test statistical comparison for the specimens manufactured at different pressures compared to a reference pressure of 1.0 N/mm^2 is given in Table 3. From this table, it can be seen that for PUR bonded specimens, the processing pressure does not result in significantly different shear strength results except in the case of edge-bonded specimens produced using a pressure of 0.4 N/mm^2. For the case of PRF crosslam bonded specimens, clamping pressure has no significant effect on shear strength performance (a minor deviation was recorded for PRF H for 0.8 N/mm^2). However, for edge-bonded specimens loaded at the end-grain, there is a significant difference when comparing a clamping pressure of 1.0 N/mm^2 with all lower pressures. When compared to the shear strength of solid wood specimens, PRF E specimens manufactured using a pressure of 1.0 N/mm^2, were slightly higher but not significantly different (Table 4). However, significant differences were found for PRF P and PUR E & PUR P specimens, as shown in Table 4.

Furthermore, the recordings of wood failure percentages confirmed the observations by Steiger et al. [14, 15] that for specimens loaded at the end-grain, the values for PUR type adhesives are generally very high and exhibit a small variation. Figure 6 presents median wood failure percentage values for different configurations of specimens manufactured using PUR and PRF adhesives with different pressures.

Generally, the lower wood failure percentages were observed for specimens manufactured with PRF than for corresponding specimens with PUR, which is in line with effect of PRF on shear strength. The lower results for the pressure of 0.6 N/mm^2 might be associated with variability within timber.

4.1.2 The effect of adhesive type

Comparison of results between PUR and PRF systems for different clamping pressures and testing configurations showed insignificant differences in corresponding samples. The ratios of PUR to PRF 5-percentile shear strengths differ in most cases by less than 10% (the exception is 22% for crosslam samples manufactured using 0.8 N/mm^2 and loaded in vertically), as presented in Table 5.

There is no general consistency in these results, however, the ratios for crosslam specimens loaded horizontally are very close to 1.00, giving an indication that adhesive type has no effect on structural bonding performance, which is confirmed by Student's t-test. It is very likely that slight differences in the ratios are determined by wood performance.

4.1.3 Effect of test configuration

For edge bonded specimens, the 5-percentile shear strength values of specimens loaded through the end-grain are 3.5 times of those loaded perpendicular to grain, which is shown in Figure 7.

The corresponding ratio for solid wood specimens loaded at the end-grain to those loaded perpendicular to grain is 2.8. When values of specimens loaded through the end-grain are compared to crosslam specimens ratios vary between 3 and 6, depending on manufacturing pressure. It should be noted that the strength ratio for crosslam specimens loaded vertically to those loaded horizontally varied between 0.64 and 1.00. It is likely that this is associated with more tilting of the V-type specimens during testing, as these specimens were more slender than the H specimens. Such a phenomenon was noticed by Steiger et al. [14, 15]. Therefore, it seems that these tests on crosslam bonded specimens placed in the shearing tool horizontally most accurately reflects the shearing strength of glue lines in CLT. In addition, the results for the H configuration were slightly more consistent than for the V configuration, as shown by the standard deviation values.

4.2 Bonding pressure and adhesive type effect on durability

Although delamination results varied 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 vast majority of cases, delamination occurred in a single 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 the CLT layers were not edge bondeded, then small gaps are present between adjacent boards in each layer. Delamination always occurred at the shortest edge board, as seen in Figure 8 (c).

It seems that median values are the most realistic measure to assess the results of the delamination tests, since the extreme results are excluded, which may otherwise skew the overall result. Therefore, the median values of total and maximum delaminations, and total and maximum wood fibre failures of split surfaces are shown in Figure 9. Although, there are no noticeable differences between the total and maximum delimitation results for PUR and PRF adhesive systems, it was observed that the highest manufacturing pressure of 1.0 N/mm^2 provided the most durable bonds. This phenomenon was slightly more pronounced for PUR.

On the other hand, the trends of wood fibre failure percentages, total and minimum, for PUR and PRF adhesive systems vary considerably. High values for PRF, above 80% for minimum wood fibre failure for all manufacturing pressures, indicate very good durability performance of PRF glue lines. For PUR, minimum wood fibre failures were noticeably low for panels assembled with pressures of 0.4 and 0.6 $N//mm^2$, suggesting poor durability. However, for specimens manufactured with higher pressures, values of wood fibre failures were much higher, up to 100% (minimum & total), which pointed out the substantial effect of bonding pressure on durability of specimens bonded using PUR adhesive. Such phenomenon might be associated with deeper glue penetration from bonded surfaces inside wood for specimens manufactured with higher pressure. For the lower manufacturing pressures when adhesive penetration is shallower, the higher surface of adhesive is directly exposed to water. Therefore, this effect of increased durability for higher bonding pressure is much more pronounced for PUR than PRF, because PUR reacts with moisture and PUR is more valuable to water action than PRF.

5. Conclusions

Based on the investigations presented in this study the following conclusions can be formulated:

- Both adhesives, PUR and PRF, produced boards with shear strength values within the requirements of prEN 16351 for all manufacturing pressures. The lowest pressure of 0.4 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 for edge bonding.
- While the PUR specimens had higher shear strength values than PRF bonded specimens when the manufacturing pressure was up to 0.8 N/mm^2, the durability characteristics in the delamination tests were unsatisfactory for PUR specimens manufactured with pressures below 0.8 N/mm^2. The PRF specimens demonstrated superior durability characteristics in the delamination tests, providing satisfactory results for the pressure of 0.4 N/mm^2 applied during manufacturing of the specimens. Furthermore, it was established that the widths of the narrowest timber elements in CLT test piece determine the depth of delamination.
- Annex D of prEN 16351:2013 specifies that loading of the parallel bonded specimens should be applied through the end-grain for testing edge bonds, however, there is lack of testing protocol, in this standard, for shear strength of surface bonds in CLT panels. It seems that the test protocol introduced in this study for crosslam bonded specimens, cut from CLT panel, and placed in the shearing tool horizontally, accurately reflects to shearing strength of glue lines in CLT. Due to the relative simplicity of this method, it may be considered as an indicator of shear strength of bonds between the layers comprising CLT.

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Table 1 Typical characteristics of adhesives for CLT manufacturing [34]

Item	Adhesive		
	PRF	EPI	PUR
Cured adhesive colour	Dark	Light	Light
Component	Liquid, two components	Liquid, two components	Liquid, single component
Solids content [%]	50	43	100
Wood moisture content [%]	6 - 15	6 -15	> 8
Target application rate (single spread) [g/m^2]	375 – 400	275 – 325	100 - 180
Assembly time [min]	40	20	45
Pressing time [min]	420 – 540	60	120
Applied pressure [N/mm^2]	0.8	0.8	0.8 - 1.4
Cost [$/kg]	4.4	7.7	10.6

Table 2 Numbers of shear tests

Bonding pressure [N/mm2]	0.4		0.6		0.8		1.0		Solid wood (unglued) (SW)
Adhesive type	PUR	PRF	PUR	PRF	PUR	PRF	PUR	PRF	
End-grain (E)	36	18	36	18	36	18	36	18	36
Perpendicular to grain (P)	36	18	36	18	60	18	36	18	36
Crosslam vertical (V)	16	34	16	32	17	30	16	22	-
Crosslam horizontal (H)	16	32	16	32	17	34	16	22	-

Table 3 Student's t-test p-values for comparison of shear tests results for manufacturing pressure of 1.0 N/mm^2 with lower manufacturing pressure for specimens produced with PUR and PRF adhesives in different configurations

Bonding pressure [N/mm^2] Adhesive type & test configuration	0.4	0.6	0.8
PUR E	0.0022	0.6956	0.6737
PRF E	0.0000	0.0000	0.0000
PUR P	0.0007	0.5111	0.0563
PRF P	0.2820	0.7588	0.0667
PUR V	0.1302	0.6126	0.1154
PRF V	0.9875	0.4426	0.9932
PUR H	0.0656	0.2599	0.3789
PRF H	0.6493	0.1923	0.0376

Table 4 Student's t-test p-values for comparison of shear tests results for solid wood specimens with glue lines manufactured with 1.0 N/mm² pressure for specimens produced with PUR and PRF adhesives loaded end-grain and perpendicular to grains

Bonding pressure [N/mm²] Adhesive type & test configuration	1.0
PUR E	0.0141
PRF E	0.1285
PUR P	0.0000
PRF P	0.0000

Table 5 PUR to PRF ratio of 5-percentile shear strength values and Student's t-test p-values (in brackets) for different manufacturing pressures and test configurations

Bonding pressure [N/mm^2] Test configuration	0.4	0.6	0.8	1.0
E	1.13 (0.0001)	1.07 (0.0000)	1.08 (0.0000)	0.87 (0.0354)
P	0.92 (0.0532)	1.04 (0.2914)	1.01 (0.0345)	0.92 (0.0331)
V	0.92 (0.6788)	0.92 (0.5347)	1.22 (0.7025)	1.13 (0.0695)
H	0.98 (0.0383)	0.96 (0.8608)	0.98 (0.1364)	1.01 (0.0965)

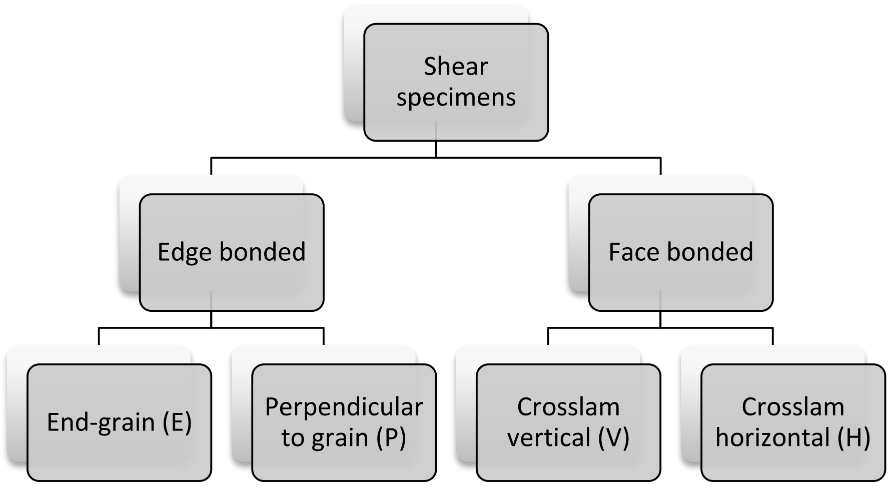

Figure 1 Schema of specimen configurations for shear tests

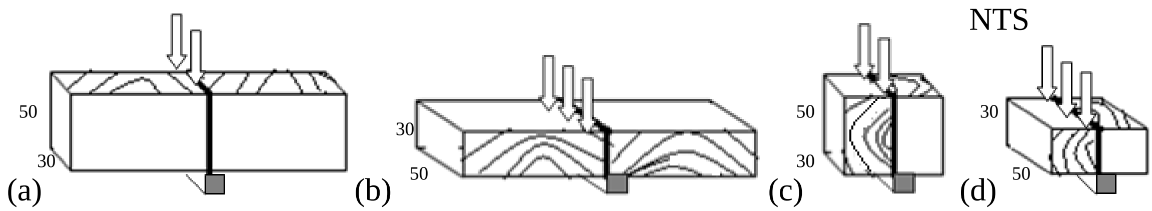

Figure 2 Shear test specimens for: end-grain (a), perpendicular to grain (b) loading, and crosslam bonded elements vertically (c) and horizontally (d) loaded (dimensions in mm)

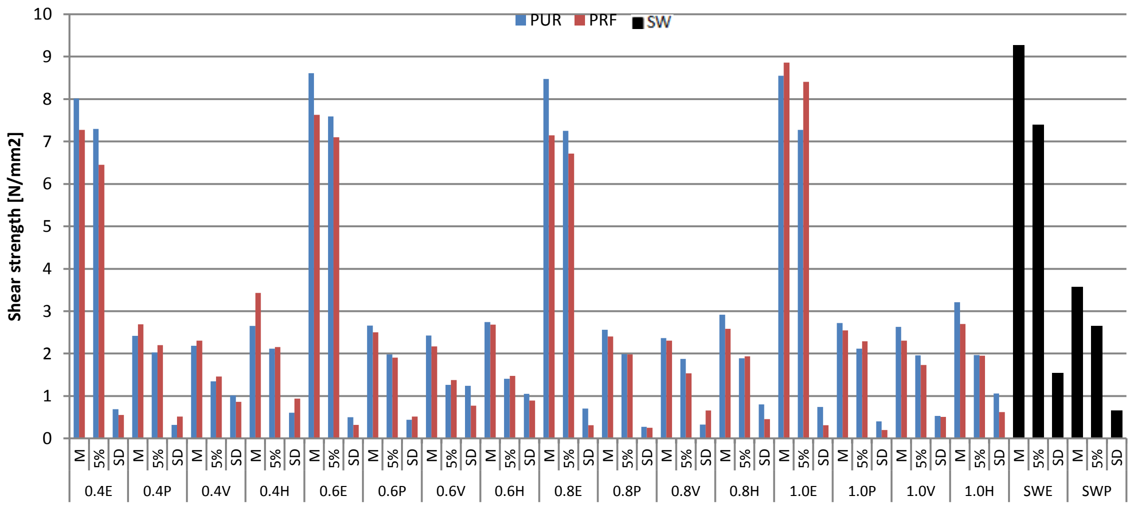

Figure 3 Shear strength values†

† Abbreviations on horizontal axis represent: number – manufacturing pressure in N/mm^2, letter - specimen configuration (e.g. 0.4E - specimen manufactured using 0.4 N/mm^2, loaded end-grain during shear test)

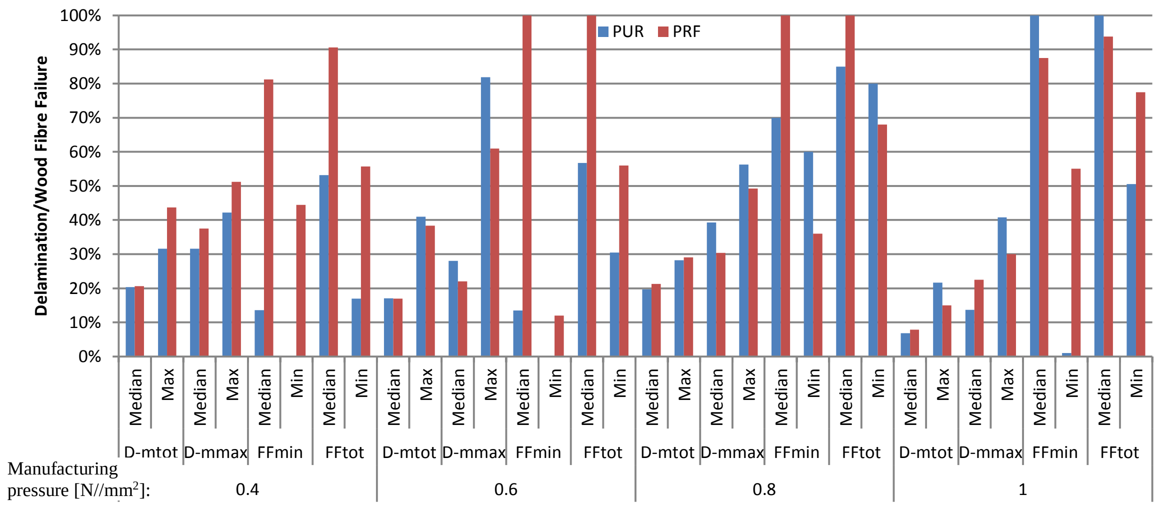

Figure 4 Delamination tests results‡

‡ D-mtot is the total delamination *Delam*$_{tot}$, D-mmax is the maximum delamination *Delam*$_{max}$

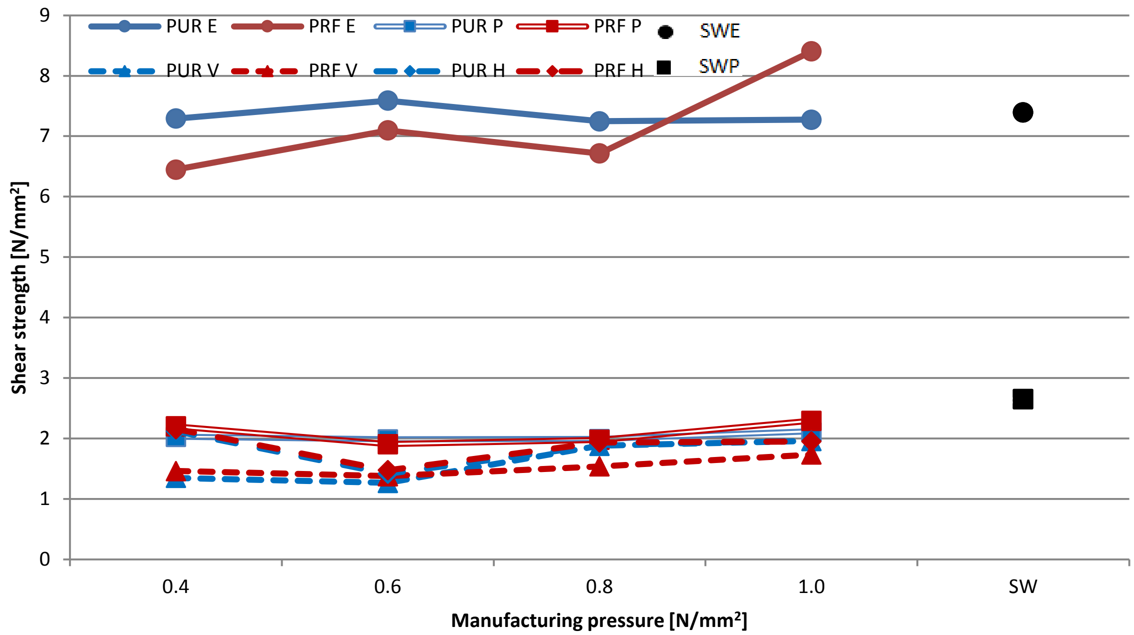

Figure 5 5–percentile shear strength values for different test configurations

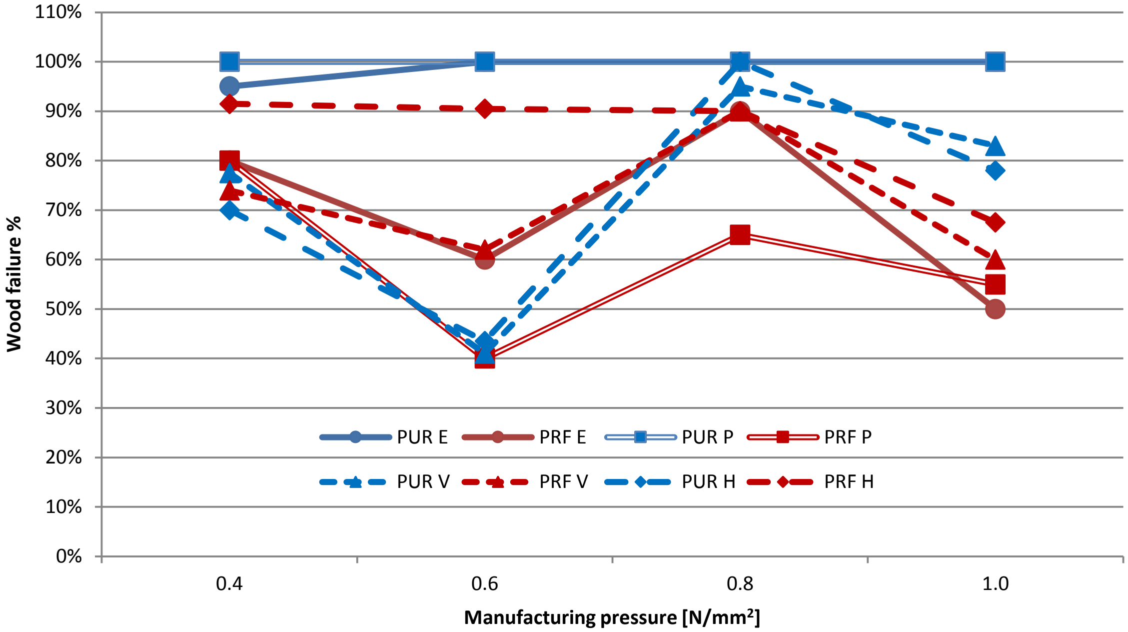

Figure 6 Median wood failure percentage values for different configurations of specimens manufactured with different pressures

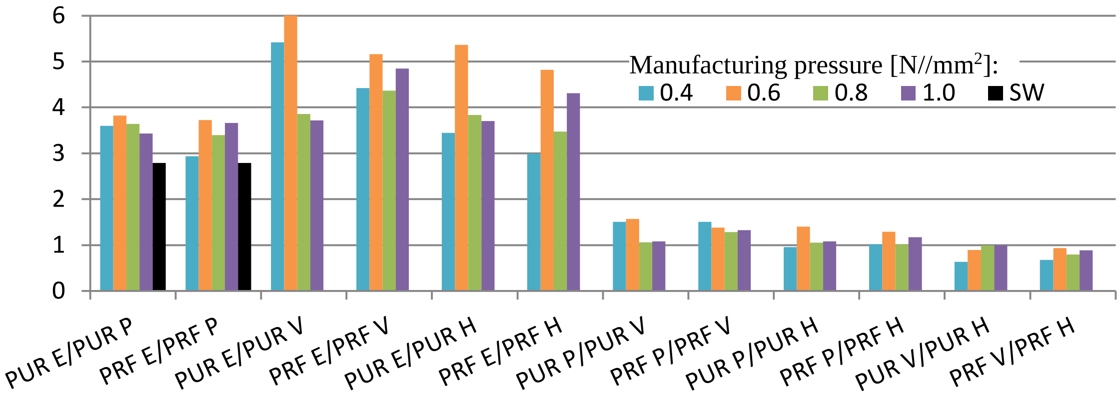

Figure 7 Ratios of 5-percentile shear strength values for different manufacturing pressures

(a)


Figure 8 Specimen for delamination test before (a) and after vacuum-pressure cycle (b, c)

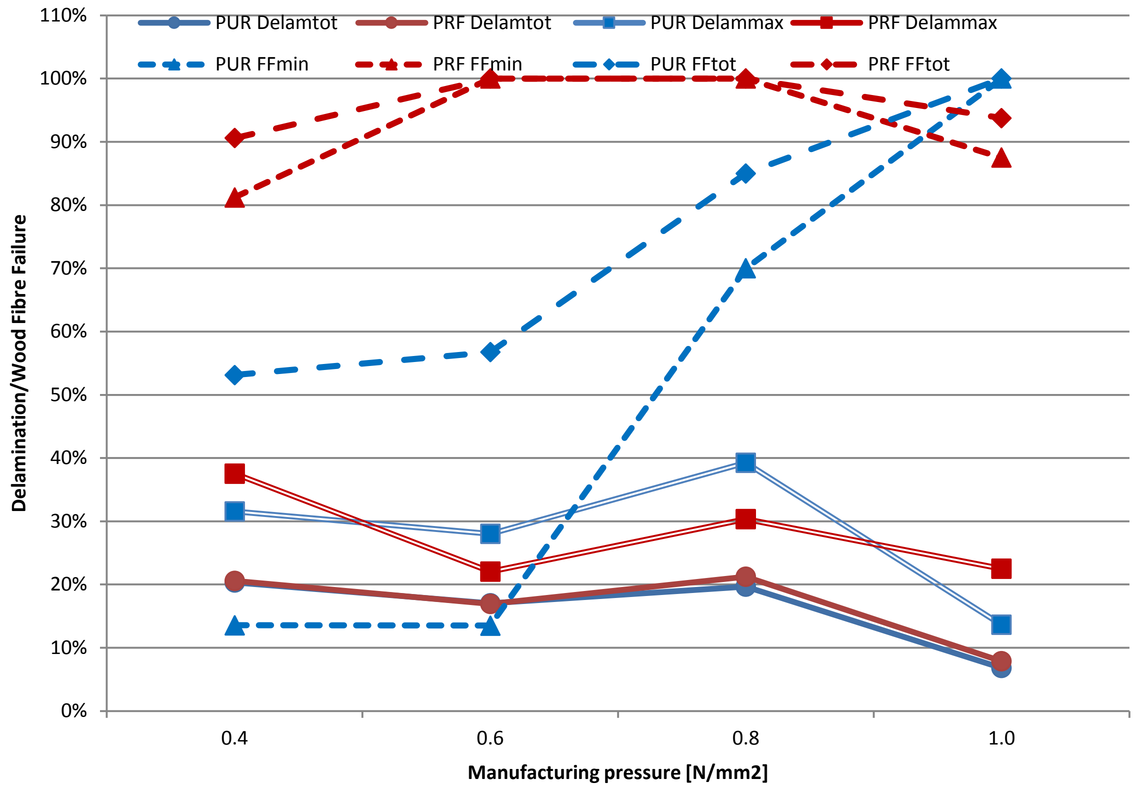

Figure 9 Median delamination and wood fibre failures values for specimens manufactured with different pressures