AN ABSTRACT OF THE THESIS OF

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Title: Effective Bonding Parameters for Hybrid Cross-Laminated Timber (CLT).

Abstract approved:

Lech Muszynski

Cross-laminated timber (CLT) is a massive engineered wood product made of orthogonally bonded layers of solid-sawn lumber, and is intended for roof, floor, or wall applications. Although it was developed in Europe in the early 90s, CLT is relatively new to North America.

CLT products must be certified for structural use. First North American product standard stipulating test methods and qualification criteria for benchmark structural properties and adhesive bond integrity in structural CLT is ANSI/APA PRG320-2012. These methods and criteria have been adapted from existing laminated timber products (glulam), sometimes disregarding substantial differences between parallel laminates and CLT, in which layers are perpendicular to each other.

From the point of view of long term sustainability of the CLT industry in North America, the critical questions are:

1. Is it possible to use low-grade timber harvested in the Pacific Northwest region in CLT products without compromising critical engineering parameters? Utilization of low-
grade lumber, which is typically under-valued, in value-added engineered products should reduce the pressure on the high end structural lumber supply and may also provide a substantial outlet for lower-grade lumber timber species, including beetle-killed pine (BKP) harvested in the affected areas.

2. Can alternative adhesive systems, currently used in related engineered wood products and manufactured by domestic industry, be successfully used in CLT production? This is an important question, and is related to the fact that polyurethane (PUR) is the primary adhesive currently used by CLT manufacturing industry, and is supplied worldwide by a single Europe-based company. This adhesive is optimized for the species commonly used in CLT products to-date. ANSI/APA PRG320-2012 standard allows alternative adhesive types (PRF and EPI are specifically named), but to-date, only one alternative (MUF) has been used in commercial products [1].

The objective of this project is to determine effective adhesive systems and bonding pressures for the hybrid cross-laminated timber (CLT) combinations. A secondary objective is to evaluate the testing methods prescribed in PRG 320-2012 for cross-laminated bond integrity.

Integrity of hybrid CLT layups was evaluated on small specimens derived from CLT billets fabricated in-house using test procedures and qualification criteria specified in ANSI/APA PRG 320-2012 section 8.2.3. Test results were compared to prescribed qualification criteria.
The Hybrid CLT combinations for this study include both structural grade lumber and low-grade lumber. For a reference species, lodgepole pine was selected, since it is a member of the US-SPF group closely related to the European species commonly used for CLT construction. The structural-grade, local species will be represented by Douglas-fir, while the low-grade species will be represented by low-grade lodgepole Pine, Douglas-fir, and Western Hemlock. The two adhesive systems investigated were 1) polyurethane-based PUR (currently the most common adhesive used by the CLT industry), which will serve as a reference system, and 2) phenol-resorcinol formaldehyde (PRF), which will represent a potential domestic alternative. PRF was chosen because it is a cold setting adhesive commonly used by the engineered wood products industry in North America; however, no CLT manufacturers utilize this adhesive system [3].

The variables included species combinations (6), adhesive types (2), and clamping pressures (3), with repetition of 9 specimens per combination coming from at least three different CLT billets. The specimen’s bond integrity was assessed by the qualification panel requirements in PRG 320-2012 section 8.2. The qualification tests are block shear and cyclic delamination. A combination must pass both of the test requirements to qualify.

The results of the study show that, of the 36 combinations, six failed the block shear test requirements and twenty-five failed the delamination test requirements. The 10 variable
combinations that passed both requirements were DDL10F, DDL40F, DPL40F, PPH10F, PPH69F, PPH10U, PPH40U, PPL10U, PPL69U, and PHL69U (see sample naming guide in Figure 19).

Initial inspection of test results show that no single variable that seems to make a significant impact on the bond integrity. It did reveal that no combinations with the use of Douglas-fir as a face material and PUR as an adhesive met the requirement, and only one combination with western hemlock as a core material met the requirements. It is evident that the delamination test was the major restriction on whether or not a combination passes the bond qualification. We believe that the adaption of a delamination test standard designed for layers with parallel grains makes the passing requirement too strict for an orthogonally bonded product.

In conclusion, there were 10 combinations that passed both bond integrity test requirements. It was unclear whether the species and/or grade combination, adhesive system, or clamping pressure made the biggest impact on the bond integrity. Relative to the reference adhesive (PUR), and species combination (lodgepole pine), the hybrid panels performed similarly and showed that certain species and/or grade combinations could pass the qualification requirements for specific requirements.

The knowledge gained by this screening study will allow further qualification testing of the passing combinations per PRG320-2012. This also has the potential to supply the
CLT manufacturing community with greater flexibility of manufacturing techniques and materials, as well as offer value to underutilized lumber.
Effective Bonding Parameters for Hybrid Cross-Laminated Timber (CLT)

by

Blake Larkin

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Blake Larkin, Author
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Effective Bonding Parameters for Hybrid Cross-Laminated Timber CLT

1. CHAPTER 1 -- INTRODUCTION

The first North American product standard for cross-laminated timber (CLT) defines it as, “a prefabricated solid engineered wood product made of at least three orthogonally bonded layers of solid-sawn lumber or structural composite lumber (SCL) that are laminated by gluing of longitudinal and transverse layers with structural adhesive to form a solid rectangular-shaped, straight, and plane timber intended for roof, floor, or wall applications [2].”

CLT is a potentially cost competitive solution that complements the existing light frame and heavy timber options, and is suitable for many applications which currently use concrete, masonry, and/or steel.

1.1. Development of CLT Industry

The material and method of building with CLT were originally introduced in Austria and Germany in the early 1990s [3]. Most of the CLT manufacturing facilities are still located in Europe, with the majority being by the technology’s origin, in a small region in Northern Europe that consists of parts of Austria, Germany, Italy, and Czech Republic. The use of CLT as a building material has spread throughout Europe, and has reached Japan, Canada, and now, the United States [1].
1.1.1. Development in EU

Today, CLT in Europe competes successfully with steel, concrete, masonry, and light frame wood structures, owing to the combination of lightness, intrinsic insulating properties, proven seismic performance, ease and short-duration of construction, which translate into low cost of erecting structures. Eight-story CLT buildings have been erected in London, UK, and in Milan, Italy. In late 2012, a 10-storey CLT Forte Building in Melbourne, Australia once became the tallest residential timber building in the world [4], despite the fact that there is not a single CLT manufacturing plant in Australia and all panels for the Forte building were shipped from Austria. In more recent news, an 18-story (about 174 feet, 53 meters) student housing building was erected on the University of British Columbia’s campus. From the time the pre-fabricated panels were delivered to the building site, the structure was completed in less than 70 days. This equates to a constructing time of about one story every four days [5].

A survey conducted by researchers at Oregon State University in 2016 was done to attain information on the variety of CLT manufacturing information. This survey revealed that 96% of CLT panels produced are custom panels (as opposed to commodity, or “blank” panels) [1].

CLT manufacturing processes and construction technologies have been developed in Europe over the last 15-20 years, despite lack of the product standard, which was drafted only in 2011 (prEN 16351:2011) [6].
1.1.2. Development in the United States

The development of CLT technology has been observed with growing interest in North America. This brought about the CLT Handbook (Canadian edition in 2011 and US edition in 2013) and the Standard for Performance-Rated CLT (ANSI/APA PRG320-2012).

The CLT Handbook is a peer reviewed information resource developed by FPInnovations, the USDA Forest Products Laboratory, the American Wood Council, APA, WoodWorks, and Forestry Innovation Investment. The handbook provides information that can be used for design and construction of CLT structures under the “alternative” path in building codes and design standards [7].

PRG320 is a product standard that prescribes requirements and test methods for qualification and quality assurance of structural CLT panels for use in Canada and the U.S. The committee tasked with creating the standard was familiar with the wood industry currently in place in the U.S., where the main massive structural wood composite had been glue-laminated beams (glulam). Due to this, many of the PRG 320-2012 qualification test methods and qualification criteria were adapted directly from the glulam industry, even though the products are vastly different.

Both editions of the CLT handbook and the PRG 320-2012 performance standard were released in the early 2000s, yet, the practical adoption of the technology had been lagging behind in 2015. At the beginning of the project, in 2014, there were only two CLT plants manufacturing certified structural panels in all of North America, StructurLam in Penticton, BC and Nordic Structures in Chibougamau, QC. Since then,
D.R. Johnson Riddle Laminators opened the first structural CLT plant in The United States in 2015 (which is located in Riddle, OR) and SmartLam has certified their CLT plant located in Whitefish, MT (which was previously producing non-structural CLT to be used for as access mats) following ANSI/PRG 320-2012 performance standard.

CLT technology in The United States is at the stage where it is being certified and adopted as an alternative building material. So far, this has been done using the CLT Handbook and the PRG 320-2012 performance standard for qualification requirements. Within these, there are building design values for six grades of pre-qualified CLT layups made from commonly found wood species and species-groups within the U.S. and Canadian timber industries. These grades can be found in Annex A of ANSI/APA PRG 320-2012, and will be discussed in Section 1.4.2.

1.1.2.1. **Pacific NW Opportunity**

The Pacific Northwest (PNW), particularly Oregon, is uniquely positioned to become a hub for the domestic CLT industry and development of domestic building technologies based on the CLT panels. This is mainly due to its close vicinity to a high potential earthquake zone along the pacific coast region, large forest land, and existing wood products industry.

Among the factors that make the PNW a potential for a CLT hub, the seismic threat is of particular importance to the entire Pacific Coast region. While California is known for frequent earthquakes due to the shallow crustal motions, Oregon and Washington, are located in the Cascadia Subduction Zone, which historically produced
less frequent but, according to the geological and paleo-seismic evidence [8], much more powerful, violent, extensive, and longer mega-thrust earthquakes due to the rapid release of energy built up over long period of time.

CLT buildings have also shown they can perform very well in severe seismic events. In 2007, a seven-story CLT building developed in collaboration between Italian research institute IVALSA and a consortium of European CLT manufacturers was successfully tested on the earthquake shake-table in Miki City near Kobe in Japan. The tri-axial record of the 1995 JMA-Kobe record was used as input of the table, representing one of the most severe earthquakes recorded in Japan [9].

Figure 1: Map showing beetle killed pine PNW and Canada [10]
According to a 2006 census, western states in the continental U.S. were responsible for 17,738 of 48,773 million board feet (BF), about 36% of the total output in the country. Of the western states, Oregon produced the most, at 6,810 million BF. Douglas-fir is the dominant western species, and in 2006, accounted for about 48% of the total softwood lumber production in the western United States [11]. The PNW and Canada also contain a large amount of beetle killed pine (BKP) throughout the PNW and Canada, which is a result of bark beetles, as shown in Figure 1 [10].

Bark beetles (Coleoptera: Curculionidae, Subfamily Scolytinae) are significant tree mortality agents in North America [10]. In the past 25 years these insects have killed over millions of acres of forests in the U.S. and Canada. The infection is caused by the mountain pine beetle (Dendroctonus ponderosae, or MPB), which has caused extensive lodgepole and ponderosa pine mortality in the western US, especially in British Columbia, Colorado, Wyoming, Montana, Idaho, Washington and Oregon [12].

While the beetles kill trees, they do not harm the quality of the wood directly. Rather, dead trees standing on stump degrade with time [13]. In pines killed by MPB and other agents, there is a characteristic set of changes that occur with time, and after about five years following mortality, much of the value of the log is lost due to stains and cracks, but not much in terms of mechanical properties [14]. In fact, prompt salvage within first three to five years after mortality returns high quality timber from mature trees in the killed stand. Massive wood products like CLT have been recognized as an excellent way to utilize large quantities of beetle-killed pines. Since structural-grade pine timber has already been used with CLT, there is little doubt that the structural-grade
timber harvested from the BKP forests within the first five years following mortality can be efficiently utilized in large quantities in quality CLT products.

Our CLT research group, focusing on the utilization of low-grade or low-valued lumber, at Oregon State University believes that CLT technology should also provide a substantial outlet for low-grade BKP timber harvested in the affected areas.

The PNW opportunity has been recognized since the beginning of this project, resulting in DR Johnson Riddle Laminators opening the first U.S. based structural CLT manufacturing plant, located in Oregon.

1.2. CLT Manufacturing Process

The CLT manufacturing sequence can vary greatly depending on the manufacturing plant. An example of a general CLT production process can be seen in Figure 2, where the process starts with winning a project bid and ends with panel installation.

A basic sequence that is generally followed for all CLT manufacturing is the steps of:

1. Lumber Preparation
2. Panel Layup
3. Panel Pressing
4. Panel Processing
1.2.1. **Lumber Preparation**

This step of the manufacturing process is meant to help ensure sufficient bond quality of the CLT panels, and includes the steps of end jointing, planing, cutting to size, and debris removal (optional).

Lumber end jointing is when the lamination’s ends are bonded together, which is a required step that typically takes place after planing.

Lumber planing is important to help provide an optimal surface for adhesive bonding. Planing creates a smooth surface by removing blemishes created from sawing.
equipment or by removing unevenness of the surface caused by alterations in the moisture content. Surfacing also removes extractives from the lumbers surface to create a more wettable bond surface [15].

Cutting the lumber (before or after planing) to size is done to ensure the length of the laminations will result in a square panel product with the pre-designed dimensions. Debris removal is an optional step of cleaning the bond surface before applying adhesive. This has been observed at some manufacturing plants, which use a vacuum device to remove dust and chips that may have been left on the surface after planing.

1.2.2. Layup

Layup is the step in which the adhesive and laminations of CLT panels are built up to form laminated layers. There is large variety of layup methods that range from a more manual approach to completely automated. Layup sequences may also change depending on the desired final product (e.g. walls vs floors/ceilings).

Manual layup usually includes manual lumber placement with a form of automated adhesive application. For manual lumber placement each layer of lumber is placed by hand (alternating with adhesive application).

Automated layup is close to an automated glulam assembly, where the one extra step used two conveyor belts to build alternating layers, where one is rotated 90 degrees to make it orthogonal. Adhesive is applied on the partial layup stack between placing these layers.
There are many different adhesive application units seen throughout the engineered wood industry, but the purpose of the equipment is to spread a uniform and appropriate amount of adhesive to the adherend’s surface [15]. Spreading techniques can be determined by the type of adhesive and product to be manufactured. Automated, adhesive extruders are most common for CLT manufacturing.

Extruders apply adhesive by means of extruding parallel lines (or threads) of adhesive on the substrate. In CLT production, this is typically done by motion of the extruder head over the CLT layers to be bonded [7]. To adjust the amount of adhesive per unit of area (spread rate), the flow rate of the adhesive or the speed of the extruder head can be adjusted.

If using a two part adhesive with a resin and hardener, the adhesive can either be mixed prior to extrusion or during pressing. To mix during pressing, the parallel drip lines can alternate between liquid resin and liquid hardener, and the adhesive mixing then takes place as the material is pressing. This method was witnessed at a CLT manufacturing facility.

1.2.3. Panel Pressing

Panel pressing is the step of clamping the layers together as the adhesive is curing. According to the survey sent out in 2016 to gain information about the CLT industry manufacturers, the primary types of CLT presses are hydraulic (67%), vacuum (25%), pneumatic (5%) [1].
Since most CLT adhesives are room temperature curing adhesives, it is important for the press to be able to maintain adequate pressures for extended periods of time. Hydraulic presses have a larger range of pressures for which panels can be pressed, and are typically capable of up to about 150 psi (1.03 MPa). Vacuum presses are limited by the atmospheric pressure, which has a maximum pressure of about 14.5 psi (0.1 MPa) at sea level.

To reduce the formation of gaps between laminations within a layer caused from horizontal slipping during pressing, certain precautions can be used to secure the panels in the horizontal direction. For hydraulic or pneumatic presses, this can be done by the addition of a side press or by securing the laminations prior to pressing with wooden dowels along the edges and/or corners.

Compared to other engineered wood products, such as plywood or OSB, CLT is relatively thick and cannot effectively use heat as a curing device for adhesive curing. This is because wood is a heat insulator, so cold setting adhesives are often used. With a cold setting adhesive, presses are designed to hold high, constant pressure, for extended periods of time. Heat setting adhesive can be used with CLT if a radio-frequency press is used, which fires radio-frequency through the wood laminations to heat the water within the adhesive at the bondlines, causing it to cure [15].
1.3. Manufacturing Parameters

Mechanical performance of CLT panels can be affected by variations in manufacturing methods or panel components. These parameters may include species and grade of the lumber, layup schedule, adhesive system, and clamping pressure.

The survey from the Wood Science Department at Oregon State University was sent to CLT manufacturers in 2016 to gain a better understanding of the types of adhesive used and the types of presses [1].

1.3.1. Species and Grades

Since CLT panels are primarily made of smaller pieces of lumber, the species and grade of lumber should have an effect on the performance characteristics of the completed panel. An example of this can be seen when comparing the 2015 NDS Supplement (Table 4A) to the PRG 320-2012 CLT standard (Table A1). In this comparison, No. 2 Douglas-fir-Larch from the NDS and the V1 graded CLT panels from PRG 320-2012 (which uses visually graded No. 2 Douglas-fir-Larch for the face layers) both have modulus of elasticity design values equal to 1.6*10^6 psi.

The two types of graded CLT panels are “V” and “E”, which are based off the method the laminations are graded: visual and E-rated (also known as machine-graded or machine stress rated) [15].
Figure 3: Required layups for corresponding CLT grades, where E utilizes MSR graded lumber and V utilizes visually graded lumber [2].

Visual grading is based on the understanding that mechanical properties of wood differ depending on many characteristics, when compared to clear lumber [15]. These characteristics can be identified visually be either trained professionals or machines. The typical wood characteristics that determine a lumbers grade are “knots, slope of grain, checks and splits, shake, density, decay, annual ring count and percentage latewood, pitch pockets, and wane” [15].

E-rated lumber, or machine-graded lumber, is a method of non-destructive testing to attain characteristics of the lumber. The two types of machine-grading in North America are Machine-stress-rated (MSR) lumber and machine-evaluated-lumber (MEL) [15]. MSR grading to attain the modulus of elasticity E is the most common method to sort lumber. MEL grading is done by evaluating some parameter, often density, and sorting based on said parameter. “Machine-grading allows for better sorting of material for specific applications in engineered structures [15].”

Species and grade can vary depending on geographic location, manufacturing plants, and mechanical requirements of the completed panel. Species used in CLT are generally softwood harvested within a close proximity to the manufacturing facility to
keep transportation and manufacturing cost lower. This creates a general trend of species within a geographical location. The differences in grade requirements between Europe and the U.S. are mainly due to differences in existing infrastructure and lumber practices. One example is the lumber practice, where in Europe, manufacturers produce a wide range of lumber thicknesses, but North America primarily produces two inch stock for structural purposes.

In Europe, the most common lumber and grade used in structural CLT manufacturing is Spruce C24, which is graded visually [16]. Some manufacturing plants also provide an option to change the grade or lumber type for the surface layer for aesthetic purposes [16]. The United States has two manufacturing plants, one utilizes layup schedules with visually graded Douglas-fir and the other uses visually graded spruce-pine-fir (SPF).

The CLT manufacturing plant in Riddle, OR, manufactures the CLT panels following the layup schedule for the CLT grade V1 [17]. All other layup schedules in PRG 320-2012 with existing design values can be seen in Table 1 of PRG 320, and are shown in Figure 3.

The survey mentioned above also revealed that global CLT manufacturing is 96% custom layup for a specific job. This means that lumber grades, sizes, and species may vary depending on the application of each CLT panel [1].
1.3.2. Layup Schedules

The Layup schedule refers to the arrangement of layers within a CLT panel. Since CLT is manufactured by laminating layers with anisotropic properties (properties vary depending on direction), loads may not transfer uniformly through the product. An example of this is shown in Figure 4, where the computer program OSULaminates was used to simulate stress distributions on a 5 layer Douglas-fir laminate (program material: Douglas-fir slice).

The layup was set with two independent stress states of 200 MPa in axial compression and 200 MPa in flexural stress. These were done to model the axial stress reaction data shown by the blue dots/lines. The colored areas show locations of tension (green) and compression (red).

In axial compression, the simulation shows the majority of the stress is resisted by the parallel layers. This would give insight as to why the 2015 NDS only takes into consideration the surface area of the layers with grain parallel to the axial compression force when determining the design values for compressive strength.

The laminate in bending also shows that most of the tension and compressive stress is carried by the face layers (top and bottom). Some load is also carried by the middle layer in major strength direction (parallel to face layers), although it is minimal. An insignificant amount of tension and compression is carried in the layers of the minor strength direction (perpendicular to face layers); however, these layers will still be used for resisting shear forces caused from bending.
The shear stress carried by the layers in the major strength direction is shear along the grains (just like in glulam laminations), however, the stress carried in the minor strength direction is rolling shear, which is a term for shear perpendicular to the grain direction. Rolling shear values are very low, by an average of 18% to 28% of the shear parallel to grain [15]. Since the 2015 NDS Table 4A design values for shear parallel to grain are not dependent on the grade of the lumber, and the rolling shear is about the same in the longitudinal-radial and longitudinal-tangential planes, it can be assumed that the rolling shear values will be very similar between different grades of lumber.

This deduction makes sense when considering the strength of wood comes from the fibers or tracheids, and when loaded in shear perpendicular to grain, their strength characteristics are not utilized. A representation of this would be to consider a bundle of straws, which would roll or slide by each other when put in shear, as seen in Figure 5.
Figure 5: Box of straws showing mechanics of rolling shear in wood.

Loads have shown to not transfer uniformly through CLT panels, and it is important to take this into consideration when designing a layup schedule to best utilize the lumbers strength properties. This is shown in the PRG 320, where the pre-qualified layup schedules V1-3 all have higher grade lumber requirements for the layers in the major strength direction, when compared to layers in the minor strength direction.

1.3.3. Adhesive System

Since CLT dimensions can only be achieved by laminating many smaller pieces of lumber together, an adhesive bond is very important to ensure load is transferred
between sections of lumber. Also, due to the common loading requirements of CLT panels (walls, floors, and roofs) the dominant force applied to a glue line is shear. These panel configurations are referred to as diaphragms or shear walls.

A diaphragm is defined as “flat structural unit acting like a deep, thin beam [18].” These have been used for floors to carry loads from within the span to the end walls. In wall applications, the diaphragms are used to resist wind loads [18].

A shear wall is, essentially, “a vertical, cantilevered diaphragm.” This is meant to transmit forces from the diaphragms, into the top of the wall, and out the bottom. This is repeated down a building until it is transferred into the foundation [18].

Examples of applied loads on diaphragms and shear walls can be seen in Figure 6.

The OSU survey showed that the primary adhesive systems in the world are the cold setting adhesives PUR and melamine urea formaldehyde (MUF), which equate to 59% and 22% of the CLT market, respectively. It should also be noted that 11% of the market is using nails or screws instead of adhesive. The use of fasteners is, by definition, not CLT; however, it is designed to serve the same purpose as a CLT panel.
1.3.4. **Clamping Pressures**

Clamping pressure is important to help ensure that a bond is not weaker than the adherend which is being bonded. There is typically a recommended clamping pressure range prescribed by the glue manufacturers.

According to the Wood Handbook, the ideal clamping pressure is able to force trapped air from between the bond surfaces, bring adhesive into molecular contact with the wood surfaces, force adhesive into the wood structure for greater surface adhesion and mechanical interlocking, squeezes the adhesive into a thin film, and hold the
assembly while the adhesive is cured [15]. A clamping pressure that is too high may have the consequence of forcing too much adhesive into the wood or squeezing too much adhesive out of the sides of the laminate, which could result in a starved bondline [15].

1.3.5. Thickness Tolerances

Control of the thickness tolerances between laminations of the same layer provides a more consistent clamping pressures during adhesive curing. This is because the press will need to provide higher forces at certain locations to close gaps.

Gaps formed by variations in thickness can be seen in Figure 7a & b. These figures show the effects of a lamination which is significantly thicker or thinner than other laminations within a layer. In these scenarios, the press will need to overcome compressive forces perpendicular to the grain in order to close the gaps.

Warp of laminations is another source of gaps, shown in Figure 7c. In this scenario, the press will need to overcome torsional stiffness of the warped laminations to close gaps.

If the press successfully closes the gaps of in these examples, the remaining bondline will have residual stresses after pressing, which could result in unpredictable bondline failures.
1.4. CLT Restrictions and Requirements in PRG 320

The PRG 320-2012 performance standard is a prescriptive standard that, not only, sets performance requirements for finished CLT panels, but also regulates and prescribes the species, grades, moisture content, thickness tolerances, and width tolerances of lumber permitted for use in CLT, as well as the prescribes adhesive qualification criteria (separate from the bond integrity performance criteria).
1.4.1. Component Requirements:

PRG 320-2012 has certain minimum requirements for components to be used for the production of CLT to help ensure that panels will meet design requirements. The two components under review are the lumber (or laminations) and the adhesive.

Lumber has requirements for species, grades, sizes, moisture content, face bonding surface, and face bonding dimensional tolerances.

Species of lumber to be used in structural CLT needs to be recognized by the American Lumber Standards Committee under PS 20 or the Canadian Lumber Accreditation Board under CSA 0141. The species must also have a minimum published specific gravity of 0.35 in the National Design Specification for Wood Construction (NDS) in the United States and CSA 086 in Canada.

Grade requirements for lumber in the parallel layers (major strength direction) is a minimum grade of 1200f-1.2E MSR or visual grade No.2. The minimum grade requirement for the perpendicular layers (minor strength direction) is a visual grade of No.3.

Size requirements for laminations are that they shall not have a width of less than 1.75 time the thickness in the major strength direction, or a width less than 3.5 times the thickness in the minor strength direction shall not have (unless the laminations are edge bonded or the interlaminar shear strength and creep are evaluated in accordance with section 8.5.5 of PRG 320-2012 and the principals of ASTM D6815), and that both directions shall not be less than 5/8 inches (16mm) or more than 2 inches (51 mm) and the lamination thickness shall not vary within the same CLT panel [2].
Moisture content at the time of CLT manufacturing must be equal to 12±3% for sawn lumber [2].

Face-bonding surfaces must be planed before bonding and must be without raised grain, torn grain, skip, burns, glazing, or other deviations that might interfere with contact between bonding surfaces. PRG also states that all face-bonding surfaces are to be free from dust and foreign matter that could be detrimental to an adequate bond. The standard suggests that lamination surfaces be planed within 48 hours of face bonding [2].

Face-bonding dimensional tolerance requirements in PRG 320-2012 state that variations in thickness along the length of each lamination and along the width of each lamination shall not exceed ±0.008” (±0.2 mm) and ±0.012” (±0.3 mm), respectively [2].

Adhesive requirements in PRG 320-2012 are typically tested by the adhesive manufacturer to be certified and approved for use in CLT. Test methods for the United States and Canada are prescribed in the standard, and are related to structural requirements and heat performance [2].

1.4.2. Structural Performance Requirements

The structural performance requirements for CLT are outlined in Table 1 of PRG 320-2012. This table has characteristic test values for CLT grades E1-4 and V1-3. The test values are shown in Figure 8, where $f_t$ is the tensile strength characteristic test value, $f_c$ is the compression strength characteristic test value, $f_v$ is the shear strength characteristic test value, and $f_s$ is the interlaminar rolling strength characteristic test
value. Each of the characteristic test values has a requirement for both major and minor strength directions [2].

<table>
<thead>
<tr>
<th>CLT Grades</th>
<th>$f_{0.05}$ (psi)</th>
<th>$E_0$ (10^3 psi)</th>
<th>$f_{t,0}$ (psi)</th>
<th>$f_{c,0}$ (psi)</th>
<th>$f_{v,0}$ (psi)</th>
<th>$f_{0.00}$ (psi)</th>
<th>$E_{00}$ (10^3 psi)</th>
<th>$f_{t,00}$ (psi)</th>
<th>$f_{c,00}$ (psi)</th>
<th>$f_{v,00}$ (psi)</th>
<th>$f_{0.00}$ (psi)</th>
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</thead>
<tbody>
<tr>
<td>E1</td>
<td>4,095</td>
<td>1.7</td>
<td>2,885</td>
<td>3,420</td>
<td>425</td>
<td>140</td>
<td>1,050</td>
<td>1.2</td>
<td>525</td>
<td>1,235</td>
<td>425</td>
</tr>
<tr>
<td>E2</td>
<td>3,465</td>
<td>1.5</td>
<td>2,140</td>
<td>3,230</td>
<td>565</td>
<td>190</td>
<td>1,100</td>
<td>1.4</td>
<td>680</td>
<td>1,470</td>
<td>565</td>
</tr>
<tr>
<td>E3</td>
<td>2,520</td>
<td>1.2</td>
<td>1,260</td>
<td>2,660</td>
<td>345</td>
<td>115</td>
<td>735</td>
<td>0.9</td>
<td>315</td>
<td>900</td>
<td>345</td>
</tr>
<tr>
<td>E4</td>
<td>4,095</td>
<td>1.7</td>
<td>2,885</td>
<td>3,420</td>
<td>550</td>
<td>180</td>
<td>1,205</td>
<td>1.4</td>
<td>680</td>
<td>1,565</td>
<td>550</td>
</tr>
<tr>
<td>V1</td>
<td>1,890</td>
<td>1.6</td>
<td>1,205</td>
<td>2,565</td>
<td>565</td>
<td>190</td>
<td>1,100</td>
<td>1.4</td>
<td>680</td>
<td>1,470</td>
<td>565</td>
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<tr>
<td>V2</td>
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<td>1.4</td>
<td>945</td>
<td>2,185</td>
<td>425</td>
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<td>1.2</td>
<td>525</td>
<td>1,235</td>
<td>425</td>
</tr>
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<td>V3</td>
<td>2,045</td>
<td>1.6</td>
<td>1,155</td>
<td>2,755</td>
<td>550</td>
<td>180</td>
<td>1,205</td>
<td>1.4</td>
<td>680</td>
<td>1,565</td>
<td>550</td>
</tr>
</tbody>
</table>

Figure 8: Table of required characteristic test values found in PRG 320-2012 [2].

Meeting these characteristic test values for the grades E1-3 and V1-3 allows CLT panels to be qualified for the design values specified in Annex A of PRG 320-2012 [2]. This Annex has design values for certain in-plane and out-of-plane properties.
1.5. Custom CLT Grades

If the prescribed layups for CLT grades E1-4 and V1-3 from Table 1 of the PRG 320-2012 (shown in Figure 3 and Figure 8) are not used, then custom CLT grades can be used if the layups undergo the necessary qualifications. The qualifications for custom CLT layups are the plant pre-qualification and qualification tests for bending stiffness (\(E_l\)), bending moment (\(f_{bs}\)), and interlaminar shear capacity (\(V_s\)) of CLT layups in both major and minor strength directions [2].

Hybrid CLT panels would be a potential custom CLT layup, which consists of varying species between layers. This would be considered a custom layup because all of the pre-qualified layup schedules in PRG 320-2012 are made with the same species in all adjacent layers.

1.5.1.1. Plant Pre-Qualification

A CLT manufacturing plant needs to be pre-qualified in order to prove that panel manufacturing equipment within the plant can produce adequate bonded laminates. This is achieved by testing “pre-qualification panels.”

The pre-qualification panels are taken from the assembly line and shall be manufactured to reflect the key characteristics of the manufacturing equipment and process [2]. Square billets with sides of 24-36 inches are extracted from the center of the pre-qualification panels to be tested for bond integrity.
1.5.1.1.1. **Bond Integrity testing**

Bond integrity testing is done to prove that manufacturing facilities can make CLT panels with sufficient bond strength and durability. The bond testing is outlined in section 6.4.3, which references sections 4.5.4.1 and 4.5.4.3 of ANSI/AITC A190.1-2007. These sections provide testing and/or qualification requirements for block shear testing, wood failure acquisition, and cyclic delamination testing of the pre-qualification billet bondlines. Both of these test methods state their use is for laminations with parallel layers, such as glulam [19].

**Shear testing** requirements outlined in section 4.5.4.1 of A190.1 state block shear testing is to be done in accordance with Test T107 from AITC Test Methods for Structural Glued Laminated Timber; however, PRG 320-2012 states that there is no minimum requirement for block shear samples. This is due to shear requirements for CLT being tested on a larger scale with short span testing. Also, there is not much statistically significant data on rolling shear for various species, which would be necessary for reference values. The purpose of the block shear test is to fail the bondline in shear in order to inspect the bondline for the percentage of wood failure to prove the bond is stronger than the wood substrate. Since there is no requirement for shear strength, there is also no option to exclude wood failure results from samples, even if the sample had relatively high shear strength.

**Wood failure** is assessed from evaluating the sheared bond areas of the block shear specimens, and is defined as the percentage of a bond area that failed in the wood fibers. The average wood failure percentage for a batch of specimens needs to be greater
than or equal to 80%, as specified in PRG 320-2012. To better understand the importance of wood failure, it is important to understand the other failure types.

Figure 9: Three adhesive failure modes, where the adhesive is dark brown, showing mostly cohesive failure (a.), adhesive failure (b.), and adherend (or substrate) failure (c.).

In general, there are three main failure modes for wood-adhesive bonding, which are: cohesive failure, adhesive failure, and adherend failure. Cohesive failure occurs when fracture propagates through the adhesive only, and means the adhesive was weaker than the substrate and bond. Adhesive failure is when all, or most, of the glue is left on one side of the fracture, which typically signifies poor bonding or poor resin transfer. Adherend failure (or wood failure in the case of CLT) occurs when the fracture propagates through the substrate, which means the glue and bond did not weaken the combined part or structure [15]. The differences in the three failure modes can be seen in Figure 9.

PRG 320-2012 has so required method for evaluation of wood failure, but the standard for evaluating wood failure is documented in ASTM D5266-13. This recommends mentally dividing a bond area into quadrants and estimating the wood failure of each quadrant to the nearest 5%. Challenges that could arise with the use of this standard are a large variation in results between evaluators (reduces repeatability), and
having trouble distinguishing between wood and adhesive, especially for clear adhesives like PUR [20].

To combat the challenge of evaluating bondlines with clear adhesives, researchers have used different methods to create contrast between transparent adhesives and wood. Some of these methods are done using fluorescence or surface stains.

Fluorescence is a property that some atoms and molecules have, where they can absorb light of a particular wavelength and re-emit the light at a longer wavelength [21]. Unlike “glow-in the dark” materials (such as phosphorescence), fluorescent materials only emit the light when they are exposed to light of a specific wavelength [22].

Fluorescent microscopy has been the most common way to create contrast between adhesive and wood while studying adhesive penetration into wood cells [23]. The basic mechanics of this method are to use a specific light source to excite a fluorescing material, and then use a wavelength selection device to filter out emitted wavelengths [21].

Adhesives can have inherent fluorescing characteristics [24] or have a fluorescing agent added [25] to create contrast. This method is relatively easy to use and inexpensive but, gives a limited depth of view and may need an altered adhesive prior to manufacturing [23].

Surface staining is a method in which the failed bond area is subjected to an agent that creates contrast between a transparent adhesive and the wood. One example of this was a study in which a solution containing pH activating dyes was used to react with variations in acidity between the wood and adhesive [26].
**Delamination** testing is done to evaluate the adhesive bond durability. Test methods are found in section 4.5.4.3 of A190.1-2007, and state that durability shall be tested with Test T110 from AITC Test Methods for Structural Glued Laminated Timber. The standard requires a maximum allowed specimen delamination of 5% for softwoods and 8% for hardwoods after one cycle. This test is important because it gives insight on how the product will react to shrinking and swelling cycles due to temperature and/or humidity fluctuations during its lifetime.

As wood absorbs water, while staying below the fiber saturation point, its dimensions change, but since wood is an orthotropic material, it changes differently in different directions relative to the grain [15]. Because of this non-uniform change in dimensions, shrinking and swelling of laminations bonded orthogonally will create internal residual stresses. This is because the layers will be trying to hold each other back from expanding or shrinking to their lowest energy state.

1.5.1.2. **Mechanical Properties Qualification**

The mechanical properties qualification section prescribes test method requirements needed to meet the structural performance levels for finished CLT product samples set in Table 1 of the PRG 320-2012 standard. The mechanical properties qualified are bending stiffness (EI), bending moment ($f_{bs}$), and interlaminar shear capacity ($V_s$) of CLT layups in both major and minor strength directions.
Even though all CLT panel layups need to be tested against the engineering benchmarks from Table A1 of the PRG 320-2012 performance standard, restrictions are still placed on the components to be used for the manufacturing of CLT panels.

1.6. Problem Statement/Opportunity

CLT is a fairly new building product in the United States. The performance standard (PRG 320-2012) and test methods are greatly derived from the existing Glulam industry, and are still in there early stages of development [27].

There are many manufacturing parameters that can affect the performance and mechanical properties of the panels. These panels are slowly being integrated into building practices with new building codes and standards, but the performance standard (PRG 320-2012) puts restrictions on the species and grades of lumber.

Grade requirements for lumber in the parallel layers (major strength direction) is a minimum grade of 1200f-1.2E MSR or visual grade No.2. The minimum grade requirement for the perpendicular layers (minor strength direction) is a visual grade of No.3. It has been shown that under certain loading conditions, the stresses on the panels are mainly carried by layers in the major strength direction. Also, that shear perpendicular to grain is roughly the same for softwoods regardless of the grade. This may provide an opportunity to use lower grade lumber in the layers that are not designed to carry loads parallel to grain.
To help keep CLT prices competitive with other building materials, manufactures strive to source CLT components from local suppliers to reduce the impact of transportation costs for lumber and adhesive components.

From the point of view of long term sustainability of the CLT industry in North America, the critical questions are:

1. Is it possible to manufacture CLT products using domestic species harvested in the PNW with a grade lower than prescribed in PRG 320-2012 without compromising critical engineering parameters? Utilization of under-valued timber in value-added engineered products should reduce the pressure on the high end structural lumber supply and provide a substantial outlet for lower-grade BKP timber harvested in the affected areas.

2. Can alternative adhesive systems currently used in related engineered wood products, and manufactured by domestic industry, be successfully used in CLT production? This is an important question and is related to the fact that currently the CLT manufacturing industry primarily uses polyurethane (PUR) supplied worldwide by a single Europe-based company. This adhesive is optimized for the species commonly used in CLT products to-date. Even though ANSI/APA PRG320-2012 standard allows alternative adhesive types (PRF and EPI are specifically named).

1.7. Importance

The importance of this research from the point of view of long term sustainability of the CLT industry in North America, is that utilization of lower grade timber in value
added engineered products is expected to reduce the pressure on the structural lumber supply and provide a substantial outlet for lower-grade beetle-killed pine (BKP) timber. The Pacific northwest, and in particular Oregon, is uniquely positioned to become the hub for the domestic CLT industry and development of domestic building technologies based on the CLT panels. CLT manufacturing brings a potential to revive forest products oriented communities across the region. Successful implementation of this research will result in hybrid CLT panels that will help in adoption of the product in mainstream domestic construction marketplace.

1.8. Hypothesis

CLT technology significantly reduces the influence of the weakest component on the overall structural performance through repetitive use of individual lumber components in a massive structural member. The project is founded on a hypothesis that this is an opportunity for the development of new, green and sustainable construction-grade structural solutions.

The hypothesis is that cross-laminated timber (CLT) panels with hybrid layups, where layers arranged from high- and low-grade lamellas, can meet the current standard requirements for critical engineering parameters as specified in ANSI PRG 320-2012 performance standard, and that adhesive systems alternative to polyurethane PUR can be successfully utilized in hybrid CLT products. The overarching goal of this project is to verify this hypothesis.
1.9 Objectives

The objective of this project is to determine effective adhesive systems and clamping pressure (adhesive spread rates and bonding pressures) for the hybrid Cross-laminated timber (CLT) combinations. A secondary objective is to help validate the testing methods prescribed in PRG 320-2012 for cross-laminated bond integrity.

The specific objectives of this study are to evaluate the bond integrity of hybrid CLT layups on a pass/fail basis following test procedures and qualification criteria specified in ANSI/APA PRG 320-2012 section 8.2.3. Hybrid CLT layups will be manufactured with varying combinations of manufacturing parameters, and the ones that pass the plant pre-qualification criterion will move to the next stage of mechanical properties qualification.
2. CHAPTER 2 - MATERIALS AND METHODS

Bond Integrity in 36 hybrid CLT layup combinations was evaluated on small specimens derived from CLT billets fabricated in-house using test procedures and qualification criteria specified in ANSI/APA PRG 320-2012 section 8.2.3. Test results were compared to prescribed qualification criteria.

There were 36 hybrid CLT layup combinations evaluated for bond integrity. These were manufactured with six species and/or grade combinations (including reference), two adhesive types, and three clamping pressures.

![Cross-laminated timber (CLT) billet diagram](image)

Figure 10: Cross-laminated timber (CLT) billet diagram

Specimens for evaluation of bond integrity were extracted from 2 ft x 2 ft (0.61 m x 0.61 m), three-layer cross-laminated billets, to realistically account for the effect of thickness tolerances between laminations within a layer (Figure 10). The billets were constructed from nominal 2 inch and 1 inch thick lumber stock shaped to a tight thickness
tolerance. Specimens for each group were extracted from three different billets containing the same combination of variables.

2.1. Variables

The variables selected for bond integrity evaluation were species and/or grade combination, adhesive system, and clamping pressure.

Species and/or grade combinations selected for bond integrity evaluation focused on timbers available in the greater Pacific Northwest region, since we were aware of three parallel studies, two conducted at Virginia Tech (VT) and one conducted jointly by North Carolina State University (NCSU) and Clemson University (CU) in South Carolina, which focused on utilization of Southeastern species in CLT panels.

Our species and/or grade combinations consisted of structural grade lumber for the face layers and underutilized, low-grade lumber for the core layers (with exception of the reference combination). Reference billets were manufactured with three layers of structural-grade lodgepole-pine, since it is a member of the US-SPF group closely related to the European species commonly used for CLT construction. Lodgepole pine will also represent the potential use of BKP in CLT, since we assume that BKP harvested within 5 years of mortality does not experience substantial degradation compared to lumber harvested from healthy stands. High-grade, local species were represented by Douglas-fir. Low-grade lumber were represented by stud-grade LP, DF, and Western Hemlock.

The two combinations of high-grade DF face with high-grade LP core, and high-grade LP face with low-grade DF core were not included.
Adhesive systems investigated were 1) polyurethane-based PUR (currently the most common adhesive used by the CLT industry), which will serve as a reference system, and 2) phenol-resorcinol formaldehyde (PRF), which will represent a potential domestic alternative. PRF was chosen because it is a cold setting adhesive commonly used by the engineered wood products industry in North America, however, no CLT manufacturers utilize this adhesive system [1].

Clamping pressures investigated cover the range of pressures used in industry: 100 psi [0.69 MPa] (current standard for hydraulic presses used in most CLT manufacturing processes), 58 psi [0.40 MPa], and 14.5 psi [0.10 MPa] (maximum pressure available with vacuum pressing used by some leading manufacturers in Europe). The performance of bond samples fabricated with intermediate clamping pressure of 58 psi was meant to provide additional insights in the overall effect of clamping pressure on the bonding quality for selected combinations.

The variables and their specific values used in the manufacturing of the CLT billets for this study are shown in Figure 11.
2.1.1. **Experimental Matrix**

The total experimental matrix can be seen in Table 1. The solid double lines are the grid for lumber species and grades for the core layer (left columns) and face layers (top rows). Inside this grid there is an internal table for clamping pressures and adhesive systems for each species/grade combination. The seven character code within the table represents the variables combination. Figure 19 on page 62 defines the characters in the variable code.

This table includes the 6 species/grade combinations, 2 adhesive types, and 3 clamping pressures, which equates to a total of 36 variable combinations. The standard
specifies a minimum of two replicate billets shall be manufactured for pre-qualification [2]; however three duplicate billets of each combination were made following the manufacturing procedure in the panel manufacturing section in Chapter 2.

Table 1: Matrix of variable combinations with their respective billet combination codes.

<table>
<thead>
<tr>
<th>Core</th>
<th>Face</th>
<th>Pressure [MPa]</th>
<th>Core</th>
<th>Face</th>
<th>Pressure [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>LP</td>
<td>DF (H)</td>
<td>0.69</td>
<td>LP</td>
<td>DP (H)</td>
<td>0.69</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PRF</td>
<td></td>
<td></td>
<td>PRF</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PUR</td>
<td></td>
<td></td>
<td>PUR</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.40</td>
<td>DPL69F</td>
<td></td>
<td>0.40</td>
<td>DPL40F</td>
</tr>
<tr>
<td></td>
<td></td>
<td>DPL69FU</td>
<td></td>
<td></td>
<td>DPL40U</td>
</tr>
<tr>
<td></td>
<td>0.10</td>
<td>DPL10F</td>
<td></td>
<td>0.10</td>
<td>DPL10U</td>
</tr>
<tr>
<td></td>
<td></td>
<td>DPL10U</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.69</td>
<td>DDL69F</td>
<td></td>
<td>0.69</td>
<td>DDL69F</td>
</tr>
<tr>
<td></td>
<td></td>
<td>DDL69FU</td>
<td></td>
<td></td>
<td>DDL40U</td>
</tr>
<tr>
<td></td>
<td>0.40</td>
<td>DDL40F</td>
<td></td>
<td>0.40</td>
<td>DDL40U</td>
</tr>
<tr>
<td></td>
<td></td>
<td>DDL40U</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.10</td>
<td>DDL10F</td>
<td></td>
<td>0.10</td>
<td>DDL10U</td>
</tr>
<tr>
<td></td>
<td></td>
<td>DDL10U</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.69</td>
<td>DHL69F</td>
<td></td>
<td>0.69</td>
<td>DHL69F</td>
</tr>
<tr>
<td></td>
<td></td>
<td>DHL69FU</td>
<td></td>
<td></td>
<td>DHL40U</td>
</tr>
<tr>
<td></td>
<td>0.40</td>
<td>DHL40F</td>
<td></td>
<td>0.40</td>
<td>DHL40U</td>
</tr>
<tr>
<td></td>
<td></td>
<td>DHL40U</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.10</td>
<td>DHL10F</td>
<td></td>
<td>0.10</td>
<td>DHL10U</td>
</tr>
<tr>
<td></td>
<td></td>
<td>DHL10U</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HP</td>
<td>PRF</td>
<td>0.69</td>
<td>HP</td>
<td>PRF</td>
<td>0.69</td>
</tr>
<tr>
<td></td>
<td>PUR</td>
<td>0.40</td>
<td></td>
<td>PUR</td>
<td>0.40</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.10</td>
<td></td>
<td></td>
<td>0.10</td>
</tr>
</tbody>
</table>

KEY
Symbol | Definition
---|---
LP | Lodgepole Pine
DF | Douglas-fir
HL | Western Hemlock
(H) | high-grade
(L) | low-grade
MPa | units of clamping pressure
PRF | Phenol Resorcinol Formaldehyde
PUR | Purbond

combinations not included in study
2.2. Raw Materials

Raw materials used in the study were donated by manufacturers in the PNW and Canada. All materials were shipped to OSU, where they were stored and processed for billet manufacturing.

2.2.1. Lumber

The Douglas-fir was donated by Swanson Group (from a mill located in Glendale, OR) in September of 2014 as a non-graded, rough-cut nominal 2”x4” material at nominal eight foot lengths. The lodgepole pine was donated by Interfor (mill located in Gilchrist, OR) in fall of 2015 graded as “common” lumber planed to nominal 1”x8” at nominal lengths of 6, 8, 12, 14, 16, and 18 feet. Western hemlock was donated from Seneca Sawmill (located in Eugene, OR) in August of 2015 as a mix of nominal rough-cut 1”x4” or 1”x6” at nominal lengths of 8, 9, or 10 feet. We also used hemlock lumber from OSU storage, which was left over from another project. The hemlock from Oregon State University and was nominal 2”x4” material at 10 feet lengths. According to the OSU faculty responsible for donating the hemlock material, the lumber was originally from Hampton Lumber’s mill in Randle, WA in 2011, and was kiln dried to a desired moisture content of 17.5%. With the exception of PHL10U1 & 2, which were made with Seneca sawmill hemlock and PUR, The hemlock from Seneca Sawmill was used for the combinations containing the PRF adhesive, and the hemlock from OSU was used to manufacture the panels bonded with PUR.
### Table: Lumber Specifications

<table>
<thead>
<tr>
<th>Field</th>
<th>Douglas-fir</th>
<th>Lodgepole pine</th>
<th>Western Hemlock (1)</th>
<th>Western hemlock (2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal dimensions (in)</td>
<td>2x4</td>
<td>1x8</td>
<td>1x4 &amp; 1x6</td>
<td>2x4</td>
</tr>
<tr>
<td>Grade</td>
<td>Ungraded</td>
<td>Common</td>
<td>Ungraded</td>
<td>Ungraded</td>
</tr>
<tr>
<td>MC</td>
<td>8-14%</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Date of arrival</td>
<td>Sept. 2014</td>
<td>Fall, 2015</td>
<td>Aug. 2015</td>
<td>2011*</td>
</tr>
<tr>
<td>Donor</td>
<td>Swanson Group</td>
<td>Interfor</td>
<td>Seneca Sawmill</td>
<td>Hampton*</td>
</tr>
</tbody>
</table>

*lumber was donated to a previous project in 2011 and leftover material was stored in an outdoor, covered environment until used in this project.

All lumber meets the dimensional requirements specified in PRG 320-2012, which can be found in Section 1.4.1, however, the Douglas-fir and western hemlock from OSU had a nominal two inch thickness, and the lodgepole pine and western hemlock from Seneca Sawmill had a one inch nominal thickness.

All lumber was stored in an outdoor, covered environment to protect from rain and sun. The project timeline weather records from weatherunderground.com [28] can be found in Appendix A.

Grading of lumber was done in-house since the lumber was not structurally graded by the lumber suppliers. The objective of grading was to reproduce the minimum criteria for CLT laminations in the face and core material specified in PRG 320.

The moisture content of all lumber was checked at the time of grading using a WAGNER MMC 220 moisture meter. This was done because PRG 320-2012 specifies all lumber at the time of manufacturing must have a moisture content of $12\pm3\%$. The moisture content of all lumber was checked at three locations along the board length, and the average was used to determine if the moisture content was within range. The moisture
content was not tested at location of knots. If the lumber was not within the permitted moisture content range, it was left in storage until the moisture content was within range.

PRG 320-2012 requires minimum grade for laminations in layers parallel to the major strength direction to be 1200f-1.2E MSR (machine stress rated) or visual grade No. 2. The minimum requirements for lamination in layers perpendicular to the major strength direction are a visual grade of No. 3 or better [2]. Lumber was graded by both visual inspection and by dynamic modulus method (meant to represent an MSR grade).

Since this study is investigating the use of “low-grade” material for layers perpendicular to the major strength direction, our grading requirements for the core of the 3-layers CLT billets was a visual grade of No.3 or \textbf{worse} and an MSR grade equivalent to No. 3 or \textbf{worse}, as specified in the 2015 NDS Supplement [2]. Lumber grading was done by graduate students and OSU summer interns, so there may be differences to lumber graded by professionals or industrial grading equipment.

Table 2: Grading rules for knot size and location for No. 2 and No.3 structural light framing lumber [29].

<table>
<thead>
<tr>
<th>Lumber Grade</th>
<th>Wide Face: Edge</th>
<th>Wide Face: Centerline</th>
<th>Holes (any cause)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. 2</td>
<td>1.25”</td>
<td>2”</td>
<td>1.25”</td>
</tr>
<tr>
<td>No. 3</td>
<td>1.75”</td>
<td>2.5”</td>
<td>1.75”</td>
</tr>
</tbody>
</table>

To improve efficiency of lumber usage, visual grading was done on sections measured to 32±1 inches. Visual grading was replicated by inspection focused on visual
defects of knot size, knot location, wane, cup, and bow. Sections containing shakes, 
checks, resin pockets, splits, were not used for manufacturing of billets. For knot size and 
location, decisions were based on the requirements in the Standard 17 Grading Rules for 
West Coast Lumber 2004, section 3: National Grades-Framing Lumber, which can be 
seen in Table 2 [29]. There was no grading rules in this section for nominal widths 
greater than four inches, so these rules were used for laminations with widths of six 
inches (hemlock) and eight inches (pine). At the beginning of the project, while the 
grading crew was still on the learning curve, all knots and their positions were measured 
with calipers and compared with the grading criteria. After becoming accustomed to the 
knot size and location requirements, not every knot was measured for knot size and 
location; however, it was used for refreshing and periodic visual grading calibration. 
Wane, cup, and bow were qualitatively assessed; sections were excluded were ones that 
may affect the panel bonding.

MSR grading was replicated using a Metriguard Dynamic modulus testing device 
(Model 340 E) to test dynamic modulus of full length boards. Cutoff values for dynamic 
modulus grading can be found in Table 3. These values are based off of the NDS design 
values from the 2015 NDS supplement for the PRG grade requirements. Deviations for 
the maximum low grade dynamic modulus and minimum high grade dynamic modulus 
were made based on the amount of lumber donated and the ratio of high-grade and low-
grade lumber.
Table 3: Comparison of NDS design values for visually graded lumber to in-house-grading dynamic modulus cutoffs

<table>
<thead>
<tr>
<th>Lumber</th>
<th>Douglas-fir</th>
<th>Lodgepole pine</th>
<th>Western hemlock</th>
</tr>
</thead>
<tbody>
<tr>
<td>NDS No. 2 Design Value [psi*10^6]</td>
<td>1.6</td>
<td>1.4</td>
<td>1.5</td>
</tr>
<tr>
<td>NDS No. 3 Design Value [psi*10^5]</td>
<td>1.4</td>
<td>1.2</td>
<td>1.3</td>
</tr>
<tr>
<td>Minimum high grade dynamic modulus for study [psi*10^6]</td>
<td>1.6</td>
<td>1.2</td>
<td>1.4</td>
</tr>
<tr>
<td>Maximum low-grade dynamic modulus for study [psi*10^6]</td>
<td>1.5</td>
<td>1.2</td>
<td>1.4</td>
</tr>
</tbody>
</table>

After lumber grading, the lumber was cut into 32” sections using a chop saw. The sections were then mixed to reduce the likelihood of one panel containing multiple sections from one board.

2.2.2. Adhesives

The reference PUR adhesive system was Purbond® HB E452 donated by Henkel Adhesives North America. This adhesive is a one-component adhesive with an isocyanate pre-polymer basis and a viscosity of approximately 14,000 cps and dries clear. Two PUR containers were donated. The first was 20 lbs of adhesive packaged in a plastic bucket and the second was 100lbs of adhesive packaged in a steel drum. The steel drum was donated when the 20 pound adhesive container expired.

The PRF used for the study was a two component adhesive donated from Hexion. This adhesive has a liquid resin (CASCOPHEN® LT-75C) with a viscosity of 275-375 cps and a powder hardener (CASCOSET® FM-282). After mixing the resin and hardener, the adhesive cures to a dark reddish brown color.
Storage of both adhesives before opening was in a climate controlled room at 5°C and 65% RH. Both parts of PRF were continued to be stored in the same room after opening. PUR was stored in a room temperature environment after opening, but was not exposed to air.

**Extracting and/or mixing adhesive** varies for PUR and PRF adhesive due to the different curing methods.

**PUR** uses moisture from the wood and air as its hardening agent, it is crucial to keep all moisture away from the adhesive. To do this, the PUR container was backfilled with dry nitrogen as the adhesive was removed.

The adhesive from the plastic bucket was extracted by use of a dispensing pump (West Systems Epoxy Pump, Resin pump in 300 Mini Pump set). To backfill with nitrogen, the system was sealed off with a plastic sheet used for vacuum bagging. A vacuum bag connector was put into the plastic sheet and connected to a dry nitrogen tank. Dry nitrogen was added to the system as needed when the adhesive was pumped out and the plastic bag would begin to deflate due to the loss of adhesive volume.
Figure 12: PUR storage and extraction of from the plastic bucket using a hand pump for extraction and nitrogen for backfilling.

Extraction of adhesive from the steel drum was done by pressurizing the drum with dry nitrogen to push the adhesive out; an illustration of this can be seen in Figure 13. The adhesive was pushed through a rigid straw that went to the bottom of the tank. With this setup, if air did get into the tank it would not come into contact with the adhesive that is being used. The tank could not withstand high pressure before the top and bottom would begin to bow out, so a pressure of 8±2 psi was used (measured with a U.S. Gauge brand dial gauge with a range of 4-100±2 psi).

PUR was extracted from the storage container by the amount needed to spread over one layer of a layup (0.17 lbs; 80 g). This was done by placing a beaker on the scale, tarring the scale, and then extracting adhesive directly into it until the desired weight was achieved.
PRF is a two component adhesive, so a resin and hardener had to be mixed before application. The data sheet calls for a resin:hardener ratio range of 1:15-1:17, so a ratio of 1:16 was used for calculations. Table 4 shows the amount of PRF resin and hardener mixed to create adhesive for one panel. Hardener and resin was weighed individually on the Mettler Teledo scale (±2.20e-5 lbs or ±0.01 grams). Mixing was done with the Kitchenaid mixer for at least five minutes, as prescribed by the data sheet. Proper ventilation is required during the mixing process, so a chemical hood system was always used during mixing.

PRF resin and hardener were extracted from their containers by the amount needed to mix adhesive for one pressing cycle (up to four panels at a time, or eight bondlines). After the total batch of PRF was mixed, it was divided into bulks 0.427 lbs.
(192 grams) for each layer of 4 ft\(^2\) bondline. This mass correlates to a spread at a rate of 100 lbs. of mixed glue per 1,000 ft\(^2\).

Table 4: Resin:hardener ratio and adhesive mix amounts for one panel

<table>
<thead>
<tr>
<th>Adhesive</th>
<th>Resin:Hardener Ratio</th>
<th>Spread Rate (lbs/1000ft(^2))</th>
<th>Resin (lbs)</th>
<th>Hardener (lbs)</th>
<th>Adhesive per bondline (lbs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRF</td>
<td>1:16</td>
<td>100</td>
<td>0.367</td>
<td>0.061</td>
<td>0.427</td>
</tr>
<tr>
<td>PUR</td>
<td>N/A</td>
<td>40</td>
<td>N/A</td>
<td>N/A</td>
<td>0.17</td>
</tr>
</tbody>
</table>

2.3. Test Specimens

Bond integrity test specimens for block shear and delamination testing were extracted from 2’x2’ billets manufactured in house with the combinations of variables shown in the experimental matrix table (Table 1).

2.3.1. Billets

Three layer 24in x 24in billets were manufactured for the study (Figure 14). The manufacturing equipment and procedures for production are explained within this section.
2.3.1.1. **Manufacturing Equipment**

The manufacturing equipment needed to produce billets can be broken into the categories of lumber preparation, layup, and pressing.

Equipment within this section is underlined.

**Lumber preparation** tools included a planer and miter saw.

The planer for thickness control and for prepping the lumber surface was a 15 inch JET planer (JET JWP-15CS). Originally, the stock planer spindle was used, which has 3 straight edge knives for cutting; however, the straight blades chipped easily when planing highly knotted lumber, so sharpening of blades was frequent. Replacing the chipped knives with a sharpened set involved indexing the individual blades to make sure each was parallel to the table within the lamination thickness tolerances (±0.2 mm). This was a time consuming process.

![Figure 14: Three layer CLT Billet illustration.](image)
To reduce cost and time necessary for knife sharpening and replacement, a Byrd helical cutter head (Figure 15; Shelix Powermatic model 15) was installed in place of the original cutter head. This uses 5 rows of 15 cutting inserts that spiral down the shaft of the cutter head. This provided easier, and more consistent blade chip repair, which resulted in a significantly shorter planer downtime (estimated reduction from multiple hours less than 30 minutes). Table 5 shows which panels were made with which planer blade style.
Table 5: Table of which billets were laminated with lumber planed with a flat knifed spindle (dark grey) and a helical knifed spindle (light grey).

<table>
<thead>
<tr>
<th>Core Layer, Species</th>
<th>Face Layer, Species</th>
<th>DF (H) Pressure [MPa]</th>
<th>LP (H) Pressure [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Adhesive</td>
<td>PRF</td>
<td>PUR</td>
</tr>
<tr>
<td>LP (H)</td>
<td>0.69</td>
<td>0.4</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>0.4</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LP (L)</td>
<td>0.69</td>
<td>0.4</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>0.4</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DF (L)</td>
<td>0.69</td>
<td>0.4</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>0.4</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HL (L)</td>
<td>0.69</td>
<td>0.4</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>0.4</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Planer maintenance was performed by OSU graduate students and faculty. Chip repair and blade replacement for the straight blades and spiral cutterhead inserts can be found in Appendix B. After blade repair, blade straightness was validated to ensure the planer blades were parallel to the planer table within the lamination thickness tolerance specified in ANSI/APA PRG 320-2012. The straightness tolerance was ±0.02 mm.

The miter saw for sizing the lumber was a DeWALT brand (model DW718) equipped with a 12 inch diameter blade with 1 tooth per inch.
Layup tools included stacking guides, metal trays, rubber mats, protective paper, an adhesive mixer, and a grooved spreading knife.

- The two 90° stacking guides were made for faster and more accurate layup of panel layers.
- The metal trays were steel or aluminum, and were used for transporting laid-up billets into the press.
- Rubber mats were placed between panels during pressing to help increase uniform pressure of the panels.
- Protective paper was used to prevent the adhesive spill out from adhering to the layup tools or pressing equipment.

The order in which the metal trays, rubber mats, and protective paper were used with the CLT billets during the pressing stage is illustrated in Table 6.

A Kitchenaid mixer (model KSM50P) was used to mix PRF resin and hardener. PUR adhesive did not require mixing, since it was a one-component system.

Five spreading methods were tested, with the goal to achieve fast and uniform spreading. Fast spreading is important since the cold setting adhesives have relatively short open assembly times. Uniform spreading of adhesive on the bondline is important because areas of higher or lower adhesive concentration may bond differently. The methods tested were using:
1. A threaded rod and rolling a measured pool of adhesive across the entire layer,
2. A threaded rod and rolling a measured pool of adhesive on individual boards,
3. A flat seven inch painters knife to spread a measured amount of adhesive across the entire layer area,
4. A flat seven inch painters knife to spread a measured amount of adhesive across an individual board, and
5. A grooved seven inch painters knife to spread a measured amount of adhesive across the entire layer area.

Using a grooved knife to spread adhesive across the entire layer was chosen from the 5 options based on adhesive application time and qualitative visual inspection of the adhesive spread consistency. This method was also low cost and easily executed by one person.

Table 6: Stacking order of material during pressing

<table>
<thead>
<tr>
<th>Stacking Number</th>
<th>Material</th>
<th>Top Area dimensions Measured to ±1</th>
</tr>
</thead>
<tbody>
<tr>
<td>...</td>
<td>Repeat layers 2-5 for pressing multiple billets</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Rubber Mat</td>
<td>25” x 25”</td>
</tr>
<tr>
<td>4</td>
<td>CLT Billet</td>
<td>25” x 25”</td>
</tr>
<tr>
<td>3</td>
<td>Protective Paper</td>
<td>&gt;25” x &gt;25”</td>
</tr>
<tr>
<td>2</td>
<td>Steel or Aluminum Plate</td>
<td>≥25” x ≥25”</td>
</tr>
<tr>
<td>1</td>
<td>Rubber Mat</td>
<td>25” x 25”</td>
</tr>
</tbody>
</table>
Adhesive mass measurements were taken using a scale (Mettler Teledo PB1502-S) with range of 1.10e-3 lbs to 3.33lbs (0.5-1510 grams) and a readability of ±2.20e-5 lbs (±0.01 grams)

Pressing equipment included an OTC 55 TON ECN Hydraulic Press using a 10000 psi limit OTC pneumatic pump (model F) and force gauge with a precision of ±10,000 lbs. The pump was connected to the building air which was supplied with an analog pressure gauge (U.S. Gauge brand) with a range of 10-200 psi and resolution of ±5 psi.

We needed to control the clamping pressure, but a direct control was not available, so a correlation was determined between the input air pressure regulator and the pressing force of the press. The uncertainty resulting from the indirect control was determined, see Appendix B for correlation procedure. The nominal clamping pressure 90% confidence intervals for the combined uncertainty of the air pressure gauge and correlation are listed in Table 7.

<table>
<thead>
<tr>
<th>Nominal (MPa)</th>
<th>Nominal (psi)</th>
<th>90% Confidence Interval (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.10</td>
<td>14.5</td>
<td>0.069</td>
</tr>
<tr>
<td>0.40</td>
<td>59</td>
<td>0.363</td>
</tr>
<tr>
<td>0.69</td>
<td>100</td>
<td>0.657</td>
</tr>
</tbody>
</table>
2.3.1.2. Manufacturing Procedure

CLT specimens used for the test were extracted from billets manufactured in house. The major steps of billet manufacturing are:

5. Lumber Preparation
   - Planing
   - Sizing

6. Adhesive Preparation

7. Layup
   - Lay bottom layer
   - Apply adhesive
   - Lay core layer
   - Apply adhesive
   - Lay top layer
   - Label billet

8. Clamping cycle
   - Loading billets into the press
   - Ramp the clamping pressure
   - Hold clamping pressure
   - Unload the press

2.3.1.2.1. Lumber Preparation

Planing was done to ensure minimal variation in thicknesses between laminations, because that could create uneven distribution of pressing force across the bond area.

Per PRG 320-2012 variations in thickness “along the length of each lamination and along the width of each lamination shall not exceed $\pm 0.008$ inches ($\pm 0.2$ mm) or $\pm 0.012$ inches ($\pm 0.3$ mm), respectively.” Since there is no requirement for average or
target thickness, there is only a requirement for variations in thickness *within* each individual lamination, not *between* laminations within a layer. For example, according to the standard, a lamination with a thickness of 2.5±0.005 inches and a lamination with a thickness of 2.0±0.005 inches can be within the same layer even though there is a 0.5 inch difference between their average thicknesses. This is because they each are within the required lamination’s allowable thickness tolerances.

For this study, a maximum thickness tolerance of X±0.008 inches (±0.2 mm) along the length and width encompassed all laminations *within a layer*, where X represents a hypothetical target thickness of the layer.

The X was hypothetical for this study because only the bondline was being tested, so only variation between the laminations was controlled.

The addition of the target thickness (X) also limits the allowable thickness variation to be constant for both directions. Because of this, the more strict tolerance (±0.008 inch or ±0.2 mm) was used for all thickness measurements.

Planing was done at a rate of 16 feet per minute. Boards were planed until bonding faces were fully surfaced. Lumber thickness was not controlled. Boards were not edge planed. Planning groups were based on original thickness, and since initial thickness varied between species, one species was planed at a time.

After planning each lumber species, thickness tolerances were verified by randomly selecting at least 5 boards from each planning group to measure variation in thickness along the length and across the width of each lamination. The thickness of each 32 inch planed section was measured, roughly, every four inches using calipers (Mitutoyo
ABSOLUTE CD-6"CX + - .001mm). The ends of the sections of lumber were not measured due to planer snipe (which is when the planer removes more material at the ends), since the changes in thickness were outside of the ±0.2 mm (±0.008”) tolerance.

Since the variation in thickness is the only concern, the calipers were tarred on the first measurement so the following measurements for each planing batch were the variation in thickness. If the highest and lowest variation measurements had a magnitude difference of 0.016 inches (0.4mm), the whole batch was sent through the planer, and the thickness measurements were repeated. This was done until all measurements were within tolerance. All planing took place within 48 hours of billet manufacturing, as prescribed in PRG-320-2012 [2].

**Sizing** of the lumber was done after thickness tolerances were ensured. The purpose of starting with 32 inch sections and cutting down to 25 inch sections was to remove the planer snipe from the ends. Each end was cut off using a DeWALT miter saw so the final lamination length was 25 inches. This was to make a CLT billet of 2 feet by 2 feet, after edge trimming.

### 2.3.1.2.2. Adhesive Preparation

Adhesive preparation was done according to respective data sheets or manufacturer recommendations, and includes spread rate calculations and manufacturing time calculations.

**Spread rates** for each adhesive were based on the material data sheet. Each adhesive comes with a range of recommended spread rate. The maximum value of each
range was used, with the reasoning that excessive adhesive would be squeezed into the internal edge gaps or out of the billet edge. The adhesive spread rates used for billet manufacturing are found in Table 8.

Table 8: Adhesive spread rates used for billet manufacturing.

<table>
<thead>
<tr>
<th>Adhesive</th>
<th>Spread Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>lbs/1000ft²</td>
</tr>
<tr>
<td>PRF</td>
<td>100</td>
</tr>
<tr>
<td>PUR</td>
<td>40</td>
</tr>
</tbody>
</table>

**Manufacturing times** were monitored to insure all panels were within the open assembly time stated in the data sheet. Table 9 shows the detailed assembly times and pressing times. According to the PRF data sheet, the open assemble time is the maximum period to spread adhesive between two layers of laminations, and should not exceed 20% of the maximum assembly time. In absence of specific instruction on the open assembly time for PUR, 20% was also used. The closed assembly time is the maximum allowable time for the layers to be laid up before clamping. Illustrations of the adhesive assembly steps are shown in Figure 16.
Step 1
Place bare layer

Step 2
Spread adhesive

Step 3
Place next layer

Figure 16: Illustration of CLT assembly time steps showing the bare layer, open assembly, and the closed assembly (left to right), where the adhesive is shown in light brown.

Table 9: Assembly and pressing times for PRF PUR adhesives

<table>
<thead>
<tr>
<th>Adhesive</th>
<th>Open Assembly (mins)</th>
<th>Closed Assembly (mins)</th>
<th>Maximum Assembly Period (mins)</th>
<th>Minimum Pressing Time (mins)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRF</td>
<td>20</td>
<td>80</td>
<td>100</td>
<td>540 [9 hrs]</td>
</tr>
<tr>
<td>PUR</td>
<td>9</td>
<td>36</td>
<td>45</td>
<td>120 [2 hrs]</td>
</tr>
</tbody>
</table>

For PRF, the open time varied with change of temperature (see Table 10); temperature was monitored with an AUBE temperature/RH device. For PUR, there was just one posted assembly time of 45 minutes.

Table 10: Open time of PRF adhesive once mixed

<table>
<thead>
<tr>
<th>Temperature</th>
<th>16 °C</th>
<th>21 °C</th>
<th>27 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Usable Life (hrs)</td>
<td>4.5</td>
<td>2.5</td>
<td>1</td>
</tr>
</tbody>
</table>
2.3.1.2.3. Layup

The layup step was the act of building up the panels layers. The major steps of this procedure were applying adhesive, orthogonally stacking the next layer of lumber, and repeating until all of the layers are built up. Once this was completed, the panel was labeled. All steps were monitored with a stopwatch to ensure that the layup procedure was completed within the allotted adhesive assembly times.

Layup schedules were created to more efficiently use certain species/grades of lumber, since in-house grading required a lot of time, work space, and storage space. For billets with low grade hemlock or low-grade Douglas-fir for the core layer, laminations within the layer were altered between low-grade and filler laminations, where filler laminations were ungraded boards of the same species. This alteration method should not have affected the bond formation in the test specimens since all laminations within a layer were planed to the same thickness tolerances and made of the same species. We assume laminations of the same species would react the same during pressing, since grade should have little effect on compression perpendicular to the grain. NDS design values for compression perpendicular to grain also show no change between grades of the same species [30]. The lamination alteration layups are shown in Figure 17, where the grey represents the filler material.
Figure 17: Lamination layup patterns for layers of low-grade Western hemlock or Douglas-fir (a.) and layers of low-grade or high-grade lodgepole pine (b.), where grey laminations are filler material.

The layup in Figure 17 was used for layers composed with low-grade or high-grade lodgepole pine. The lumber was donated as nominal eight inch widths (which is technically 7.25”), so to manufacture billets with a width of at least 24 inches, 3.5 boards were used. The extra half board was ripped long ways and used as filler.
The specimen extraction diagram for panels manufactured in this manner was also changed to account for the difference, shown in Figure 18. These figures show that the locations for delamination specimens were moved while still keeping a similar spread between the specimens. Location for block shear specimens were changed very little.

![Diagram](image)

**Figure 18:** Comparison of pre-qualification billet specimen extraction locations for PRG 320-2012 (a.), and the altered locations for billets manufactured according to Figure 17a (b.), where a=4±1 inches and L=24-36 inches.

**Applying adhesive** was done using a grooved seven inch painters knife to spread adhesive across the entire layer area.

**Orthogonal stacking** of layers between applying adhesive was done until the 3-layerd panels were built up. All faces of the lumber to be glued were swept off with a handheld broom before the layup step to remove dust from lumber planing and sawing.

**Panel Labeling** was done to include the unique panel code and the date of pressing. The CLT manufacturing variables and unique panel code, “Panel Id”, are shown in Figure 19.
a. Face Layers
Douglas-fir (High)
Lodgepole Pine (High)

Core Layer
Lodgepole Pine (Low)
Douglas-fir (Low)
Hemlock (Low)
Lodgepole Pine (High)

Adhesive Types
PRF
PUR

Pressure (MPa) [psi]
0.69 [100]
0.40 [58.0]
0.10 [14.5]

b. Figure 19: The explanation of the panel ID labeling code and block shear and delamination specimens.
2.3.1.2.4. **Pressing**

Pressing was the final step of the billet manufacturing process. The key components are loading the press, ramping the pressure, holding the pressure, and unloading the press.

**Loading the press** followed the stacking instruction in Table 6. The order of billets in the press was the order of layup completion from bottom to top, since they were placed in the press as their layup was completed.

**Ramping the Pressure** was done by activating the pneumatic pump connected to the press. The peak clamping force was controlled with the input air pressure, following the calibration method in Appendix C.

**Holding the pressure** to allow the adhesive to cure was done by leaving the hydraulic pump activated for the entirety of the clamping cycle. This made up for pressure drops caused from the CLT billets creeping under pressure, which would result in a lowered clamping pressure.

Clamping times were specified in the manufacturer data sheets. The PRF billets were held under pressure for at least 9 hours, and the PUR panels were held under pressure for at least 2.5 hours.

**Unloading the press** was done after the adhesive had cured. The panels were stored for a minimum of one week before bond integrity testing, as per recommendations from the adhesive manufacturers.
2.4. Specimens

Specimens for block shear and delamination testing were extracted from the billets and machined to geometries specified by standard test methods referred to by PRG 320-2012.

2.4.1. Specimen Geometry

**Block shear** specimens followed the “stair step” sample type from AITC Test T107-2007 [19], referred to by PRG 320. This is shown in Figure 20. The layers were oriented so the outer layers were tested in shear perpendicular to grain.

![Figure 20: Stair step specimen geometry specified in AITC Test T107 Shear Test method (a.) and comparison to actual 3-layer specimen (b.).](image-url)
Delamination specimen geometry is specified in T110 [19], and was originally designed for glulam beams, so the specimen size requirements are 3 inch long sections of the beam with a depth of at least 6 inches, or the full depth of the member section if the total depth is below 6 inches. Since CLT is a panel product with orthogonally bonded layers, rectangular prisms of three inch by three inch by the lesser of six inches or the panel depth were cut from the billets. All billets were constructed with three layers of nominal 1 inch or 2, so the entire thickness was used in delamination evaluation. The sample geometry can be seen in Figure 21.

![Figure 21: Delamination specimen geometry (a.) and examples of specimens with pine cores (b.) and hemlock cores (c.)](image)

2.4.2. Specimen Extraction

Three specimens for each test method were extracted from every billet, according to the PRG-320 diagram for extracting specimens. This can be seen in Figure 22, where
“B” represents block shear samples and “D” represents delamination samples. Variations to this schematic were made to avoid edge gaps and allow more efficient uses of manufacturing material.

![Block Shear and Delamination Specimen Locations](image)

**Figure 22:** Original qualification panel sample extraction diagram from PRG 320.

Edge gaps were avoided due to complications that could arise from poor load transfer between core laminations during block shear testing, as illustrated in Figure 23, where the thick black line represents an edge gap and the colored sections represent the portion of the bondline under shear stress. In this figure, speculation shows why an edge gap parallel to the load direction would likely not have an effect on the effective bond area, but an edge gap perpendicular may decrease the effective area if the gap is not glued or perfectly tight. Because of this, all core layer edge interfaces were avoided in the
extraction of block shears. The tolerances for the y-axis listed at the top of Figure 23 were increased to ±2 inches to avoid core layer edge interfaces.

Figure 23: Presence of lamination edge in block shear specimens parallel to bondline (left) and, the undesirable, perpendicular to bondline (right).

As mentioned before in section 2.3.1.2.3 on page 59, more efficient use of low-grade hemlock and Douglas-fir was done by altering laminations with graded and filler material within a layer. For billets manufactured this way, the panel extraction schematic was altered to the extraction schematic shown in Figure 24, where the grey laminations represent the filler material.

They were then labeled using the code explained in Figure 19, found on page 62.
To extract samples, the edges of the panels were first trimmed and squared using a right angle slide and a Grizzly bandsaw (model G0640X) with a blade with 3 teeth per inch. All of the extraction measurements were taken to ±1/8 inch. The billets were divided into three strips, A, B, and C, following the diagram in Figure 25 and procedure in Figure 26. Initially, three cuts were made on each side of the A, B, and C strips using the bandsaw with an attached fence parallel to the blade. Once all billets were cut into the
three sections, the bandsaw fence was set to three inches from the blade and strips A, B, and C were cut to the same width.

Figure 25: Locations of strips A, B, and C used to extract specimens from billets.

On each strip, the location of the delamination and block shear samples were labeled following the schematic in Figure 24. After labeling, the delamination and block shear sections were cut from the strips using a DeWALT miter saw with a 12 inch diameter blade with 1 tooth per inch. For block shear specimens, a two inch section of the strip was removed and for delamination specimens, a three inch section of the strip was removed. The remaining 3”x3”xT (where T equals the panel thickness) sections are the final delamination specimen form, but the 2”x3”xT block shear sections were processed into the stair step specimen dimensions (Figure 20 on page 64).
The “stair step” block shear samples were manufactured with the Grizzly bandsaw. The first cut was trimming the 3” dimension of the cubes to 2.25”. Then cuts were made following the three step process in Figure 27 to get the stair step geometry. Care was taken to cut to the bondline but not through it. If cuts to the bondline were too shallow, corrections were made using a razor blade or sandpaper. All samples were inspected before testing.
2.4.3. **Block Shear (AITC Test T107-2007) Test Procedure**

The block shear test procedure followed AITC Test T107-2007. This test is used to assess the bond resistance to shear loading of the bondline by calculating the percentage of wood failure on the bond area after shear testing.

This test was originally designed to evaluate the face bond quality by means of shear strength and wood failure percentage for specimens that have grain parallel to the shear direction [19]. The test procedure involved destructive shear test focused on single bondline and inspection of failure plane for evaluation of wood failure percentage.

Inspection of failure planes was done by taking photos of bond areas and using image software to calculate the percentage of wood failure.
2.4.3.1. **Test Equipment**

The test apparatuses described in AITC T107 are a shear tool (similar to the one found in ASTM D905) and calibrated ram. A diagram of the example shear tool can be found in Figure 28.

![Shear tool diagram](image)

**Figure 28:** Shear tool used for AITC T107. Drawing taken from ASTM D905-2008

The calibrated ram used for control of the extension and data acquisition was an Instron system. The system included an Instron frame (model 5582Q5749), load cell (Range of $\pm 22480$ lbf (±100 kN) with the resolution of $\pm 2.25 \times 10^{-4}$ lbf (±1e-3 N)), and software package (Bluehill 2).

Calipers with a precision of $\pm 0.001$ mm was used (Mitutoyo ABSOLUTE CD-6"CX) were used for bondline area measurements.
An iPhone 6 camera with 8-megapixel iSight camera and 1.5µm pixel size was used to take bond area mages for wood failure analysis [31].

A fiber optic light source (Olympus LG-PS2-5) was used to inspect shear-failed bondlines containing PRF adhesive.

A UV Light source (Stocker and Yale halo light with two UV light bulbs) was used to create contrast between PUR and wood substrate. The inner most bulb was labeled as 973-365 9611, but there was no label on the outer bulb.

2.4.3.2. Test Procedure

The block shear test procedure followed AITC Test T107-2007. This test is used to assess the bond integrity of the bondline by calculating the percentage of wood failure on the bond area after shear testing. This procedure was broken into two parts: shear testing and inspection of the shear plane.

2.4.3.2.1. Shear Strength

The basic test procedure was to:

1. Measure the bondline area
2. Place the sample into the testing device
3. Preload the sample to 75±75 N
4. Load until failure (full separation of the sheared plane).
5. Data analysis

(1.) Sample bondline area dimensions were measured using Mitutoyo ABSOLUTE CD-6"CX calipers with a precision of ±0.001 mm. To calculate the area, the
average of two measurements taken from the ends (to account for non-parallel faces) in each direction were multiplied.

(2.) Each sample was inserted into the shearing device so that the face layer was loaded perpendicular to grain direction and the core layer was parallel to grain direction, as shown by the red arrows in Figure 29a. This was done so help prevent deep rolling shear into the core layer that could interfere with the bondline of the other face layer. The test fixture also supported a reactive force perpendicular to the grain direction of the core layer to resist the moment created by the shear forces, which is represented by the blue arrows in Figure 29a.

Figure 29: a. is the sample loading (a), where the red represents the shear force and the blue represents the opposing moment created from the shearing forces, and b is the block shear test fixture and loading design.
(3.) Once loaded in the fixture, the shear head was manually lowered until the bondline was preloaded to $75 \pm 75$ N of shear force, to remove slack from the testing system. After the manual preload, the test was engaged via the BlueHill software.

The test was conducted at a rate of 0.035 in/min (0.9 mm/min). Since T107 has no prescribed load rate, the tested load rate was based on ASTM D1037-2012, which has a speed of loading requirement of 0.24 in/min (0.6 mm/min) $\pm 50\%$ [32].

(4.) The test was run until the bondline could no longer carry load, or until the shearing tool had reached its maximum length of travel. If the shearing tool had reached its maximum travel length without failing the bondline, the test bondline was removed from the sample population.

All tested samples were stored in a way to protect the failed surface until image acquisition of the bondlines took place.

(5.) The maximum average shear strength of each bondline was determined by dividing the maximum shear force measured by the Instron system by the bond area calculated from the bond area measurements. This can be seen below in Equation 1.

$$\tau_i = \frac{F_{\text{max}}}{A}$$

Where,

$\tau_i$ = mean shear strength of one bondline at the max shear load.

$F_{\text{max}}$ = maximum shear force

$A$ = bond area
Since there is no minimum shear strength qualification in ANSI A190.1-2007, the shear strength values were used to assess the general distributions of properties of the samples.

2.4.3.2.2. **Inspection of the shear plane**

Wood Failure in the shear plane was calculated using image analysis of pictures of the fractured bond areas. This method relies on contrast between the adhesive and wood color.

An image of all four shear planes per specimen was taken with an iPhone camera focused using the tap to focus feature with auto HDR (high dynamic range) turned off, and taken roughly 2±1 inches from the bond surface.

To create contrast between the transparent PUR adhesive and the wood substrate, the wood substrate on the bond area was coated with a 0.5% safranin solution in DI water, and images were taken while the PUR on the bondline fluoresced from exposure to a UV light source.

The bond area was coated using a small paint brush, then dabbed with a clean paper towel. Care was taken to not damage the bond area. The liquid dye cannot penetrate the PUR adhesive, but will stain the wood fibers, so dabbing the bond area removes the dye from the areas of adhesive.

For PUR, images were taken when the bondlines were only subjected to UV light. The UV light source was a “halo” UV light, so the camera lens was placed at the center of the light source as both were facing the bond surface. Due to the halo light geometry, a
camera stand was used at a distance of roughly 2 inches from the bond area (this distance varies due to uneven bond fracture surfaces). The entire setup was inside a dark room with no other light sources present. An example image of a bond surface with PUR fluorescing under UV light can be seen in Figure 30a.

![Images](image1.png)  
**Figure 30:** Semi-automatic image analysis procedure executed in ImageJ software package to calculate the percentage of wood failure of specimens bonded with PUR adhesive

The inherent dark color of the PRF adhesive provided sufficient contrast between it and the wood substrate for effective analysis without color enhancement. To reduce shadows from the uneven fracture surface during image acquisition, a mixture of natural light, overhead light, and fiber-optic gooseneck light was used. The light aperture could be adjusted to change the light brightness. The direction of the light source was adjusted for each specimen to avoid shadows cast from complex bondline failure cause from a mix of rolling shear failure and tensile failures. The constant variation in lighting direction also thwarted attempts at using a camera fixture due to its own shadows, so pictures were taken free-hand. The inconsistent height of the photos should not affect the WF% test results since this method uses a ratio of wood to adhesive per photo.
The wood failure percentage in the shear plane for all block shear specimens (PUR and PRF) was determined using semi-automated image analysis procedure executed in ImageJ software package (IJ 1.46r) developed by the National Institutes of Health [33]. The software was used to convert the bondline image’s pixels into their corresponding red (for PRF) or green (for PUR) greyscale values. The greyscale values for each image were then sorted using a built in thresholding tool. A histogram tool can then be used to count the pixels at each greyscale value from 0 to 255. The steps of the process can be seen in Figure 30 for PUR bonded specimens and Figure 31 for PRF bonded specimens. To calculate the wood failure, the amount of pixels within the thresholding range was divided by the total amount of pixels in the bond area. The steps to manually use the software and the Java script executing this procedure is attached in Appendix E. To ensure accuracy for PRF specimens, bondlines were visually inspected as the thresholding range was being manually selected.
Analysis of wood failure was done by using ImageJ software for measuring quantities and the java code for deriving quantities. The ImageJ software was used to count the pixels for both wood and adhesive, and the java code was used for calculating the percentage of wood failure from the pixel count.

\[ WF_i = \frac{p_a}{p_a + p_w} \]

Where,

- \( WF_i \) = wood failure percentage of bondline “i”
- \( p_a \) = number of pixels that are adhesive
- \( p_w \) = number of pixels that are wood

ANSI A190.1-2007, referred by PRG 320, prescribes a minimum average wood failure percentage of ≥80%.

2.4.4. Delamination test (AITC Test T110-2007)

This test is used to measure the effects of accelerated weathering procedure on bondlines of glued laminated timbers using a vacuum-pressure-soak/rapid drying cycle.

2.4.4.1. Test Equipment

The test apparatuses (prescribed by the AITC Test T110-2007 test procedure) include a pressure vessel system and a drying oven. The pressure system needs to be able
to generate and withstand a vacuum of at least 25 in. of mercury (12.3 psi or 0.0846 MPa) and pressure of at least 75 psi (0.517 MPa) gauge pressure. The drying oven needs to maintain a temperature of approximately 160 °F (71°C) and RH conditions such that the samples can dry to within 15% of their original weight within 10-15 hours.

The vacuum/pressure system used in this project is a pressure tank equipped with vacuum and pressure connections to the building air lines and with a MARSH analog vacuum/pressure gauge with a vacuum range of 0-30±5 in. Hg (0-14.7±2.56 psi or 0-0.101±0.0169 MPa) and a pressure range of 0-150±5 psi (0-1.03±0.0345 MPa).

To dry the delamination blocks, a GRIEVE drying oven equipped with a Weston temperature gauge with a range of 50-300 °F (10-149 °C) and a resolution of ±2 °F (±1.1 °C). This oven model was equipped with an exhaust fan to create forced air circulation.

A Mettler Teledo PB1502-S scale with a range of 0.5-1510 grams and a precision of ±0.01 grams was used to take mass measurements of the delamination blocks during all stages of the testing procedure.

2.4.4.2. Test Procedure

The delamination test procedure followed AITC T110-2007 test procedure, which is designed to determine the effects of accelerated cyclic exposure on the bondline of glued laminated timbers specimens using vacuum-pressure-soak followed by rapid drying. For CLT qualification testing per PRG 320, AITC T110 is limited to one cycle of vacuum/pressure soak followed by one rapid drying.

The basic steps to the delamination testing are as follows:
1. Vacuum/Pressure Soak Cycle

1.1. Record specimens’ initial mass
1.2. Load specimens into vessel
1.3. Apply 25±5 in Hg. (12.3 psi or 0.0846 MPa) Of vacuum for 30 minutes
1.4. Apply 75±5 psi (0.517 MPa) of pressure for 120 minutes
1.5. Remove specimens and record their wet mass

2. Rapid Drying

2.1. Load specimens into preheated oven with forced air circulation at 160±5°F
2.2. Periodically measure the weight of the samples until the dry mass is within 15% of the initial mass
2.3. Measure delamination of the specimens’

Before loading the samples into the vacuum/pressure vessel, (1.1) each of the samples’ initial mass was recorded, this will later be used to determine if the drying process is complete. Small stickers were placed between each block to allow maximum exposure to water. (1.2) The samples were then submerged in water in a weighted metal cage to prevent them from floating and (1.3) placed under a vacuum of 25±5 in. Hg for 30±5 minutes. Next, (1.4) the samples were pressurized at 75±5 psi for 120±5 minutes. The pressure system could not account for hysteresis, so the pressures were monitored and adjusted during the cycles.

Once the vacuum/pressure cycle was complete, (1.5) the wet mass was recorded and the (2.1) samples were placed in an oven at 160±5°F. Samples placed in the oven had a minimum of two inches between them to allow air flow between all sample faces, as specified in the T110 test method [19].
Within the designated 10 to 15 hour drying time, the samples were removed from the oven and the mass was recorded, roughly, every hour until the mass of the specimens had dropped to within 15% of the original mass. Once the specimens had dried to within 15% of their initial mass, delamination was measured immediately using a ruler with a ±1mm precision. Delamination was defined as any separation at the bondline that was not a result of wood failure, and was not at a wood defect location. Each bond line of each face was measured for delamination length and total bondline length [34].

Analysis of delamination was dividing the total delamination length by the total bondline length to get the percentage of delamination. ANSI A190.1-2007, referred by PRG 320-2012, prescribes a maximum delamination for any one specimen cannot exceed 5%. If this happens, the sample fails the bond integrity qualification test. Examples of delamination at the bondline can be seen in Appendix F.

2.4.5. Evaluation of ANSI/APA PRG 320-2012 test procedures

A secondary objective of this study was to help validate the testing methods prescribed in PRG 320-2012 for cross-laminated bond integrity, since our research team was some of the first practitioners of the standard. While interpreting the language within PRG-320-2012 and the referred standards and test methods, notes were taken on issues and difficulties experienced.

2.4.6. Expected results

The results of the screening test were used to select adequate combinations of species, adhesives, clamping pressures for future full-scale mechanical and physical tests.
At this stage, clearly incompatible combinations will be screened out and excluded from test matrices of the full-scale testing. It is important to note that combinations qualified for clamping pressure below one atmosphere may be warranted in the future using more economical vacuum pressing modes (currently used by such leading European manufacturers as Binderholz and KLH in Austria, MERK in Germany, and Schilliger Holz in Switzerland).

The results of validating the test standard will provide feedback to the PRG 320-2012 committee that can be used in future versions of the standard.
3. CHAPTER 3 –RESULTS

The results of the block shear and delamination tests for all combinations are summarized in Figure 35.

The color scheme of Figure 35 is such that grey represents results which are not required for bondline integrity qualification per PRG 320-2012, blue represents combinations that have passed block shear or delamination tests, red represents combinations that have failed block shear or delamination tests, and the green highlighting columns represent the combinations that have passed both tests.

3.1. Block Shear Test

The results for the block shear test results are provided separately for shear strength and wood failure categories.

3.1.1. Shear Strength

Figure 35a. shows the average shear stress for all of the combinations; however, there was no minimum shear stress requirement in the ANSI PRG 320-2012. The mean shear strength was 489 psi (3.37 MPa) with an average coefficient of variation of 26.9%, and no apparent outliers.

3.1.2. Wood Failure Fraction

Figure 35b shows the average wood failure fraction for each of the combinations. 30 of 36 combinations tested met PRG 320-2012 wood failure percentage qualification
criteria (average WF% ≥80%). The six failing combinations were DHL10F (79.9%), DHL69F (74.7%), PPH40F (76.0%), PHL40F (63.6%), DHL10U (79.5%), and PPL40U (78.9%). The passing and failing combinations can also be seen in Figure 32.

![Figure 32: Variable combination pass and fail results for block shear test requirements.](image)

A histogram summarizing WF% for all tests makes it apparent that the WF% distribution is highly skewed (Figure 33) and cannot be well described by a mean, which is a parametric descriptor of normal distribution.
Figure 33: Histogram of wood failure percentages of all specimens.

3.2. Delamination Test

Figure 35c shows the delamination test results for all combinations. In contrast to the WF\% criterion referring to the mean WF\% value, the PRG 320-2012 qualification rule refers to the maximum delamination in the sample which cannot be larger than 5\%, therefore, in Figure 35c, the principle set of bars (red or green) are the maximum delamination per sample set, and the grey bars are the combination’s mean delamination. The combinations meeting the PRG 320-2012 delamination qualification criteria are marked green and the failing combinations are marked red. The columns that appear to be empty are those that showed very little or zero delamination.

11 of 36 combinations tested met PRG 320-2012 delamination percentage qualification criteria (max specimen delamination ≤5\%). These eleven combinations were
DDL10F, DDL40F, DPL40F, PPH10F, PPH69F, PPH10U, PPH40U, PPL10U, PPL40U, PPL69U, and PHL69U. These combinations can also be seen in Table 11.

Since all delamination blocks from a sample set needed to be less than 5% (rather than an average less than 5%), further breakdown of Figure 35c can be shown in Figure 37. This includes a delamination histogram for each of the variable combinations, which is normalized to all of the delamination data (shown by the grey bars). The arrangement of histograms is set up so each of the quadrants represent combinations that have the same face species and adhesive system, where the top left, top right, bottom left, and bottom right are DF-PRF, DF-PUR, LP-PRF, and LP-PUR, respectively. The bins on the x-axis are set up so that a bin with the range of 2.5-5, excluding the maximum bin limit value, so a failing combination is that which has a value in any of the bins of 5-7.5 or higher. A passing combination is indicated by the green checkmark, and the failing combinations by the red x.

Further observation of Figure 37 reveals that of the 11 passing combinations,

- 3 have DF face and PRF adhesive
- 0 have DF face and PUR adhesive
- 2 have LP face and PRF adhesive
- 6 have LP face and PUR adhesive
- 4 were pressed at 0.10 MPa
- 4 were pressed at 0.40 MPa
- 3 were pressed at 0.69 MPa

Looking at the above summary, one can see that the combination PPLxU (where the x represents any clamping pressure) passes the delamination requirements for all
clamping pressures. It also shows that DxxxU combinations all fail the delamination requirements.

Table 11: Passing and failing combinations for delamination testing

![Table Image]

All delamination results were pooled to create the histogram in Figure 34 to reveal the overall distribution of the delamination values. Similarly to WF%, the distribution is strongly skewed. However, in this case the skew is towards the lower end of the distribution. The majority of samples have a delamination of 0%.
3.3. Combined Tests

In order for a combination to be considered qualified per PRG 320-2012, both of the wood failure and delamination requirements must be met. The 10 combinations that passed both of these tests were DDL10F, DDL40F, DPL40F, PPH10F, PPH69F, PPH10U, PPH40U, PPL10U, PPL69U, and PHL69U. This is shown by blue boxes in Table 12 or the highlighted green columns in Figure 35.

Table 12 shows that no combinations containing DF as face material and PUR adhesive (DxxxU) pass the bond integrity qualification. 10 of the 36 combinations included in this study passed both criteria. The combination PPLxF also fails at every clamping pressure. Furthermore, only one combination containing hemlock as a core passes the bond integrity qualification requirements.
Table 12: table of results showing passing (blue) and failing (red) combinations

<table>
<thead>
<tr>
<th>Core</th>
<th>Pressure [MPa]</th>
<th>DF (H)</th>
<th>LP (H)</th>
<th>Face</th>
</tr>
</thead>
<tbody>
<tr>
<td>LP (H)</td>
<td>0.69</td>
<td>PRF</td>
<td>0.69</td>
<td>PRF</td>
</tr>
<tr>
<td></td>
<td>0.40</td>
<td>PRF</td>
<td>0.40</td>
<td>PRF</td>
</tr>
<tr>
<td></td>
<td>0.10</td>
<td>PRF</td>
<td>0.10</td>
<td>PRF</td>
</tr>
<tr>
<td>LP (L)</td>
<td>0.69</td>
<td>PRF</td>
<td>0.69</td>
<td>PRF</td>
</tr>
<tr>
<td></td>
<td>0.40</td>
<td>PRF</td>
<td>0.40</td>
<td>PRF</td>
</tr>
<tr>
<td></td>
<td>0.10</td>
<td>PRF</td>
<td>0.10</td>
<td>PRF</td>
</tr>
<tr>
<td>DF (L)</td>
<td>0.69</td>
<td>PRF</td>
<td>0.69</td>
<td>PRF</td>
</tr>
<tr>
<td></td>
<td>0.40</td>
<td>PRF</td>
<td>0.40</td>
<td>PRF</td>
</tr>
<tr>
<td></td>
<td>0.10</td>
<td>PRF</td>
<td>0.10</td>
<td>PRF</td>
</tr>
<tr>
<td>HL (L)</td>
<td>0.69</td>
<td>PRF</td>
<td>0.69</td>
<td>PRF</td>
</tr>
<tr>
<td></td>
<td>0.40</td>
<td>PRF</td>
<td>0.40</td>
<td>PRF</td>
</tr>
<tr>
<td></td>
<td>0.10</td>
<td>PRF</td>
<td>0.10</td>
<td>PRF</td>
</tr>
</tbody>
</table>
Figure 3.5: Results for average shear stress (a.), average wood failure (b.), and delamination (maximum and average) (c.).
Figure 36: Box and Whisker plots of wood failure data for each combination, where red represent the combinations that failed (had an average WF% less than 80%). See Figure 35b for comparison.
Figure 37: Delamination histograms normalized to a histogram of all of the combinations. The green box containing a P and a red box containing an F represents passing of failing, respectively.
3.4. Evaluation of ANSI/APA PRG 320-2012 test procedures

The committee tasked with evaluating and updating the PRG 320 product standard had been meeting during the final year of the project. The notes taken by our research group on interpretation and execution of test methods prescribed in PRG 320-2012 were being communicated to the committee during their reviewing process.

3.4.1. T107: Shear Test

A complication that arose while using the block shear method for CLT was that the sample did not always fail in just shear. This is because the block shear test method was designed for laminations to be tested in shear parallel to the grain, which is only true for one lamination of a bondline during shear testing of CLT specimens. Many of the samples showed signs of failure in compressions perpendicular to grain [19], tension perpendicular to grain, and, in rare cases, compression parallel to grain. Compression failure perpendicular to grain can be seen at the top of Figure 38e. Failures of tension perpendicular to the grain can be seen in a, c, d, e, and f. Compression failure parallel to grain was much less common, but can be seen in b. During testing of this sample, the movement limit of the test device was reached before the bondline of interest failed, and in doing so, damaged the other bondline on the sample. Both were excluded from the sample population. There were also signs of tensile failure perpendicular to the grain near the bondline causing peeling of the lamination. This is harder to see, but early signs are visible at the bondline in d.
These failure mechanisms contributed to ductile (non-brittle) failure behavior during bondline shear testing. This resulted in many tests carrying load long after peak strength was achieved. Examples can be seen in Figure 39, where the blue plot is a brittle failure and red and orange plots are ductile failure.
Figure 39: Load versus displacement plots for a sample showing brittle-failure (blue) and two samples showing ductile failure (red and orange). A line was added to the scatter plots to better differentiate the each plot.

3.4.2. $T110$: Delamination Test

This will be reviewed in the Discussion section below.
4. CHAPTER 4 –DISCUSSION

The objective of this project was to determine effective adhesive systems and bonding parameters (adhesive spread rates and bonding pressures) for the hybrid Cross-laminated timber (CLT) combinations. A secondary objective was to help validate the testing methods prescribed in PRG 320-2012 for cross-laminated bond integrity.

In this section, the results presented in the previous section are discussed and interpreted in the context of these specific objectives.

Initial inspection of the results in Figure 35 reveal that the primary discriminating criterion for qualification of CLT combinations per PRG 320-2012 product standard is the delamination test, and that there is not any single variable that has a definite impact on the bond integrity qualification tests.

4.1.Block shear Test

The block shear testing discussion is broken into the two categories of shear strength and wood failure fraction. Block shear testing prescribed by PRG 320-2012 only has passing/failing criterion for wood failure fraction, not for shear strength.

4.1.1. Shear Strength

Shear strength results in Figure 35a show little effect of species combination, clamping pressure, or adhesive type to the average shear strength of a sample. There was also a very high average coefficient of variation, which could be caused by the competing
failure modes (rolling shear, compression perpendicular to grain orientation, and tension perpendicular to grain orientation), which are present in cross-laminated bondlines.

4.1.2. Wood Failure Fraction

Out of the three manufacturing variables (species combinations, adhesives, or clamping pressures) it is hard to say which had a larger impact on the wood failure results.

For species combinations, there is not significant difference between using DF or LP as a face material, since both are used as face material for three of the six failing combinations; however all three failures with LP face material were manufactured with a clamping pressure of 0.40 MPa. These results can be seen in Figure 32 on page 85.

Considering just the two adhesive types, four of the six failures were combinations manufactured with PRF adhesive.

Clamping pressure also does not seem to have any obvious effects on the likelihood of a combination passing the wood failure analysis. Two of the failed combinations were from billets clamped at 0.10 MPa, three at 0.40 MPa, and one at 0.69 MPa.

All wood failure fraction test data is presented in a box-whisker plot format in Figure 36, where the whiskers present minimum and maximum values for each combination, the bottom and top of the box represent 25th and 75th percentile of WF% values within the combination and the centerline represents the median (as in Figure 40).
Figure 40: Box plot diagram for wood failure data shown in Figure 36.

If the qualification criterion referred to the median rather than to the mean WF% value for combinations, the fraction of passing combinations would increase to 32 of the total 36 tested. Four of the combinations disqualified with the PRG 320-2012’s WF% ≥80% criterion would qualify with median ≥80% principle; however, two of the combinations passing the PRG 320-2012 criterion would be disqualified using the median principle.

4.2. Delamination Test

While considering viable species combinations, there were none that passed at all clamping pressures and adhesive combinations; however PPLxU combinations pass at all
three clamping pressures. Combinations with two passing clamping pressures are DDLxF, PPHxF, and PPFxU.

Further breakdown of core material shows the passing rate for low-grade DF is 33%, high-grade LP 66%, low-grade LP is 33%, and low-grade HL is 8.3%.

The delamination results do show that, for our sample combinations and manufacturing methods, there is no clear trend for which adhesive is more suitable, since out of the eleven passing combinations, five were PRF and six were PUR. Figure 37 also shows that PUR does not pass any of our combinations with DF face material, and that the histograms appear to be very scattered (could be due to scarce sample sizes). The delamination test results in Figure 37 show that PRF works similarly with combinations manufactured with either DF or LP Faces, and with any of the three clamping pressures.

There is also no clear relationship between maximum delamination and clamping pressure, since the number of passing variable combinations manufactured with clamping pressures of 0.10, 0.40, and 0.69 MPa is 4, 4, and 3 of, respectively.

While evaluating the median delamination values in Figure 35c, there does appear to be a relationship between clamping pressures and bond durability. This is shown in combinations DHLxF, PHLxF, DDLxU, DPLxU, and DHLxU, where the median delamination percentage decreases with increased clamping pressure.

Figure 41 shows box-plots that compare the delamination data for different parameters within each variable. All other parameters are pooled in these comparisons.

The figure shows the two adhesive types performed similarly, with PUR data having a larger 75th percentile and maximum value. For clamping pressures, the high and
intermediate levels produced very similar box-plots, but the lowest level had a median delamination greater than 0% and a higher 75\textsuperscript{th} percentile. The species/grade combinations with lodgepole pine as a face species all had medians equal to zero and low or zero 75\textsuperscript{th} percentile values, but the combinations with Douglas-fir as a face species had medians greater than zero and higher 75\textsuperscript{th} percentile.

Figure 41: Box and whisker plots comparing delamination results of each manufacturing parameter.

Most of the combinations passing the delamination test requirements were manufacturing with lodgepole pine as the face species. This may be due to the lodgepole pine laminations being half the thickness of the Douglas-fir laminations.

Research on edge delamination of composites used in the aerospace industry has shown that the energy release rate for the formation of a delamination scales with the
laminations thickness [35] [36]. If this holds true for CLT composites, layers manufacturing with 1.5 inch thick laminations would be twice as likely to delaminate as layers manufactured with 0.75 inch thick laminations.

If the delamination criteria for Canada (maximum specimen \( \leq 10\% \)), or Europe/Japan (maximum specimen delamination \( \leq 10\%; \) maximum bondline delamination \( \leq 40\% \)) was used, the number of combinations to pass the delamination qualification would increase to 17 of 36. This can be seen in Figure 42.

![Figure 42: Specimens passing European, Japanese, and Canadian delamination criteria.](image)
4.3. Combined Results

Since the delamination test results were the major factor on whether a variable combination passed the bond qualification requirements, only one combination passed the delamination requirements but failed the wood failure requirements. This is the combination PPL40U, which had an average WF of 78.9% and a maximum delamination of 2.1%.

Species combinations with cores of low-grade hemlock only had a pass rate of 8.3%, which is the lowest compared to combinations manufactured with cores of low-grade DF (33%), high-grade LP (67%), and low-grade LP (25%), as seen in Table 12 and Figure 35.

Comparing adhesive types of combinations which passed both qualification tests, five were manufactured with PRF and five with PUR.

There are very small differences between passing patterns for combinations with varying clamping pressures, since of the ten passing combinations, four were manufactured with 0.10 MPa, three with 0.40 MPa, and three with 0.69 MPa.
Figure 43: Results while passing combinations with one failed specimen less than 7.5% (orange bars). Yellow columns are passing combinations. This can be compared to Figure 35.
Figure 44: Delamination histograms showing which combinations only have one failure, as depicted by the orange checkmarks. Can be compared to Figure 37.
4.4. Evaluation of Test Standards

Since CLT is a relatively new material to North America and being evaluated on the first version of the CLT product standard, there have been very few practitioners of the following the qualification requirements and test methods prescribed in PRG 320-2012.

The test methods for the qualification billets are referred to in ANSI/APA PRG 320-2012 section 8.2.3. Starting in this section, the chain of referral to the test methods is PRG 320-2012 8.2.3 > PRG 320-2012 6.4.3 > ANSI/AITC A190.1-2007 Sections 4.5.4.2 and 4.5.4.3 > AITC Test Methods for Structural Glued Laminated Timber Tests T107 and T110. Test T107 is the block shear method and T110 is the delamination method.

Altogether, this is a 4 level reference that makes it challenging for practitioners to accurately follow the standard test methods.

4.4.1. T107: Block shear Test

Some of the obstacles of the prescribed shear test method were time consuming extraction of specimens due to complicated geometry, no prescribed load rate, no exclusion rules of potential outlying data, and no mention of assessing knots in a bondline area.

Shear specimens showing ductile failure behavior is most likely caused by soft wood, in general, exhibiting similar strength properties (same magnitude) for
compression perpendicular to grain, shear perpendicular to grain, shear parallel to grain, and tension perpendicular to grain. When using the block shear method on cross-laminated layers, all of these weaker mechanical properties are competing, which causes failure modes other than pure shear. This is not typically a problem when dealing with parallel to grain shear blocks, since compression parallel to grain is generally significantly higher than shear parallel to grain.

The T107 block shear test’s minimum wood failure requirement is an average of 80%, but as we can see in Figure 45b, the data sets do not have a normal distribution. This could pose a problem because and average is a descriptor used to describe statistically normal data. Also due to the non-normal data, it is hard to determine if there is a significant difference between a passing and failing variable combination. For example, DHL10F failed with an average wood failure percentage of 79.9% and DHL40F passed with an average wood failure of 80.1%. The lack of normality also makes it more challenging to determine outlying data from a combination set.

To reveal the overall distribution of the shear strength and wood failure percentage test results, all data was pooled together and plotted as a histogram in Figure 45. The wood failure histogram shows fairly normal data with a slight right skew, while the histogram for WF shows highly left skewed data. The highly skewed data
4.4.2. T110: Delamination Test

The major obstacle of performing this test method was that AITC T110 describes no clear definition of what is to be considered delamination. There are cases when large openings between laminations makes both the presence and measuring of delamination very obvious, but there are also cases where the crack is very thin (only visible with the use of a magnifying lens) and at a very shallow depth (~1-2 mm). These cracks may also have various amounts of wood fibers that can be hard to see.

Also, Figure 35 shows that the delamination testing is the major constraint for passing the CLT bondline qualification. This could be due to strict requirements that give no option to exclude potentially outlying specimens or because the test was not designed for cross-laminated layers.

If we were to consider allowing samples with just one failing specimen with the delamination percentage between 5% and 7.5%, there would be four more
combinations passing the delamination test (DDL69F, PPL10F, PPL69F, and PPH69U). These combinations can be seen in Figure 44 and are represented by orange checkmarks or by the orange bars in Figure 43c. If these combinations were to pass the delamination requirements, the additional combinations that would pass the pass the overall bondline qualifications are represented by the yellow columns in Figure 43. This increases the number of qualified combinations from 10 to 14, but also shows that the combinations DDLxF and PPHxU pass the delamination requirements at any clamping pressure.

Table 13: Radial and tangential shrinkage values for screening study test species [15].

<table>
<thead>
<tr>
<th>Species</th>
<th>Shrinkage (%) from green to ovendry moisture content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Douglas-fir, Coastal</td>
<td>Radial: 4.8, Tangential: 7.6</td>
</tr>
<tr>
<td>Western Hemlock</td>
<td>Radial: 4.4, Tangential: 7.1</td>
</tr>
</tbody>
</table>

The higher failing rate could be due to the test requirements being made for parallel laminated structural wood composites, such as glulam. This could cause higher levels of delamination because wood does not exhibit uniform shrinking and swelling due to changes in moisture content, but has different shrinkage values for
longitudinal, radial, and tangential directions. From green to oven-dry, most species shrink longitudinally between 0.1% and 0.2%, which is significantly lower than that of radial and tangential shrinkage (see Table 13) [15]. These differences may create larger residual stresses during the rapid drying cycle for CLT than it would for samples with parallel laminations (glulam).

Delamination test methods and qualification criteria prescribed by the European and Japanese CLT standards are less strict.

The European CLT standard (prEN 16351:2011) prescribes a delamination test method similar to that of AITC T110, however the qualification criteria are less strict, with a maximum specimen delamination equal to 10% and a maximum bondline delamination in the cross-ply equal to 40% [6] [27]. The Japanese CLT standard (JAS Standard for CLT (MAFF Notification 3079)) prescribed test method is less harsh and has a more lenient delamination criteria than AITC T110 [27].

*A conference call with the PRG 320-2012 Bond Integrity Task Group took place on 12/20/2016 to discuss the evaluation of CLT bondline durability. This will not be included in this thesis, but adds merit to the discussion of adjusting the requirements.*
4.5. Sources of Variation

Some aspects of the manufacturing and testing procedures may have had an effect on the variation in the results.

While manufacturing CLT billets in house, there was low control over the spread rate within a CLT bondline. This was because the lab was not equipped with high precision adhesive spreading equipment that you would typically find in a commercial CLT manufacturing facility.

A source of variation in the delamination test results for specimens manufactured with the layup schedule in Figure 18b (page 61) may be caused by no delamination specimen being extracted from the center of the billet.

Also for delamination specimens, every crack on the bondline that was not caused by wood failure was considered delamination, even if the length and depth of the crack were very small (≤3mm). These cracks are still defined as delamination, but there may be different delamination criteria used by certified testing agents.
CHAPTER 5 – CONCLUSION

The objective of this project was to determine effective adhesive systems and clamping pressures for the hybrid cross-laminated timber (CLT) combinations. A secondary objective was to help provide practitioners on the testing methods and qualification criteria prescribed in PRG 320-2012 for bond integrity in cross-laminated.

All conclusions regarding integrity of adhesive bond in CLT are made for hybrid CLT billets manufactured in-house, and tested and evaluated according to the ANSI/APA PRG 320-2012 section 8.2.

The principle conclusions regarding the bond integrity in hybrid layups are that, while it is possible to produce CLT billets sufficient bond quality, it is difficult to identify a set of manufacturing parameters that would guarantee success with substantial constancy.

5.1. Block shear Test Results

The conclusions for the block shear test results are provided separately for shear strength and wood failure categories.

The passing criteria prescribed in ANSI/APA PRG 320-2012 for the block shear tests is an average wood failure of ≥80% for each combination.
5.1.1. Shear Strength

There are no shear strength requirements for CLT clock shear specimens used for pre-qualification bond integrity testing, however, benchmark shear values for the layups are provided in the CLT standard grade description (Table 1 of PRG 320-2012, also referred to in Figure 8 on page 24) to be used for computation of design values by engineers. These tabular values refer to the stress maximum value of pure shear.

In this study, block shear methods adopted from glulam standards produced complex ductile failure modes that are difficult to interpret.

5.1.2. Wood Failure Fraction

30 of the 36 variable combinations met the minimum wood failure fraction criteria for block shear specimens.

The six failing billet variable combinations were DHL10F (79.9%), DHL69F (74.7%), PPH40F (76.0%), PHL40F (63.6%), DHL10U (79.5%), and PPL40U (78.9%).

5.2. Delamination Results

Delamination test results were the critical discriminating factor for the pass/fail bond integrity qualification test requirements. Only one combination passed the delamination test requirements and failed the block shear test requirements.
The 11 of 36 test combinations that passed the delamination met requirement were DDL10F, DDL40F, DPL40F, PPH10F, PPH69F, PPH10U, PPH40U, PPL10U, PPL40U, PPL69U, and PHL69U.

The large number of delamination samples failing the qualification criteria could be a product of laminating thick, cross-laminated layers. Cross-laminated layer bondlines (compared to parallel laminated layer bondlines) are exposed to greater residual stresses from thermal and moisture expansion, and thicker bondlines have been shown to be more likely to delaminate than thinner bondlines (when cross-laminated) [35] [36].

5.3. Combined Results

PRG 320-2012 specifies that samples must pass both bondline qualification tests (block shear and delamination) in order to meet the requirements of the plant pre-qualification. These tests are conducted on a pass/fail basis.

Effective adhesive systems and clamping pressures for hybrid CLT layup schedules, containing low- and high-grade layers in the minor strength direction, are listed in Table 14. These combinations passed both prequalification bond integrity tests per ANSI/APA PRG-320-2012.
Table 14: Hybrid CLT layup schedules with effective adhesive systems and clamping pressures.

<table>
<thead>
<tr>
<th>Face Species</th>
<th>Core Species</th>
<th>Adhesive</th>
<th>Clamping Pressure (MPa)</th>
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5.4. Test Standards

The principle conclusions from the practitioner evaluation of bond integrity testing procedures for CLT pre-qualification billets are that bond integrity test methods adapted from existing wood composites, which have a parallel grain orientation relative to adjacent layers, may not produce results that accurately depict the bond performance of specimens exposed to shear and durability testing.

The notes taken during translation and execution of the prescribed test standards have been submitted to the 2017 PRG 320 revision committee.
5.4.1. **T107: Block shear Test**

A large portion of CLT specimens tested per T107 block shear test method show signs of compression failure perpendicular or parallel to grain, or tensile failure perpendicular to grain.

5.4.2. **T110: Delamination Test**

The T110 delamination test for CLT specimens show a possibility that the criteria determined for glulam are too harsh for cross-laminated timber samples. This is most likely because the orthogonally bonded layers do not exhibit uniform shrinking and swelling from changes in moisture content, since there are different shrinkage values for longitudinal, radial, and tangential directions.

Both the European CLT standard (prEN 16351:2011) and The Japanese CLT standard (JAS Standard for CLT (MAFF Notification 3079)) prescribed qualification criteria that less strict than AITC T110 [6] [27].
6. BIBLIOGRAPHY


7. APPENDICES

Appendix A provides weather data for Corvallis, OR, during the outdoor storage of raw lumber to be used for manufacturing CLT billets for plant pre-qualification bondline testing following ANSI/APA PRG 320-2012. All lumber was shielded from rain and sun during outdoor storage.

Appendix B describes the detailed process of replacing planer blades that were chipped during the manufacturing of CLT billets to ensure they were sharp and parallel, in order to generate a good bonding surface that meet lamination thickness tolerance requirements (based on PRG 320-2012).

Appendix C describes the procedure used to generate the billet manufacturing pressure control with the hydraulic pumps input air pressure. Since this is an indirect method of ramping the pressure, uncertainty of the correlation between input air pressure and clamping force was calculated using statistical software.

Appendix D lists the input code used in the statistical software (RGUI 64 bit) package to determine the confidence intervals for each of the nominal clamping pressures used in CLT billet manufacturing procedure.

Appendix E describes the image analysis procedure used for calculating the wood failure fraction of tested block shear bondlines, and provides the java script used to control the image analysis software (ImageJ).

Appendix F shows example images of delamination specimen bondlines and states their delamination length recorded during bond integrity testing.
# Table of Appendices

<table>
<thead>
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<th>Section</th>
<th>Appendix</th>
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<tr>
<td>7.1</td>
<td>Appendix A: Weather data for Corvallis, OR, from September, 2014, through December, 2016, which pertains to the storage conditions of the lumber used in the hybrid CLT billet manufacturing.</td>
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<td>7.2</td>
<td>Appendix B: Planer maintenance procedure</td>
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<td>Appendix C: Calibration procedure for generating an indirect control over the clamping pressure during CLT billet manufacturing.</td>
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<td>Appendix D: RGui (64 bit) script for estimating the confidence intervals for clamping pressures</td>
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<td>Appendix E: Calculating wood failure fraction of block shear specimen bond areas using image analysis</td>
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<td>7.6</td>
<td>Appendix F: Bondline delamination example images with their corresponding delamination length and percentage.</td>
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Appendix A: Weather data for Corvallis, OR, from September, 2014, through December, 2016, which pertains to the storage conditions of the lumber used in the hybrid CLT billet manufacturing.

Hybrid CLT billets, to be tested according to PRG 320-2012 plant pre-qualification, were manufactured in-house using donated lumbers. The lumber species were Douglas-fir, lodgepole pine, and western hemlock.

The Douglas-fir was donated by Swanson Group (from a mill located in Glendale, OR) in September of 2014 as a non-graded, rough cut nominal 2”x4” material at nominal eight foot lengths. The lodgepole pine was donated by Interfor (mill located in Gilchrist, OR) in fall of 2015 graded as “common” lumber planed to nominal 1”x8” at nominal lengths of 6, 8, 12, 14, 16, and 18 feet. Western hemlock was donated from Seneca Sawmill (located in Eugene, OR) in August of 2015, an. We also used hemlock lumber from OSU storage, which was left over from another project. The hemlock donated from Seneca Sawmill Company as a mix of nominal rough cut 1”x4” or 1”x6” at manufacture designated lengths of 8, 9, or 10 feet. The hemlock donated from Oregon State University and was nominal 2”x4” material at 10 feet lengths. According to the OSU faculty responsible for donating the hemlock material, the lumber was originally from Hampton Lumber’s mill in Randle, WA in 2011, and was kiln dried to a desired moisture content of 17.5%. The hemlock from Seneca Sawmill was used for the combinations containing the PRF adhesive, and the hemlock from OSU was used to manufacture the panels bonded with PUR.
Table E1: summary of information on the lumber donated for billet manufacturing

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<td>Aug. 2015</td>
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</table>

*lumber was donated to a previous project in 2011 and leftover material was stored in an outdoor, covered environment until used in this project.*

All lumber was stored in an outdoor, covered environment to protect from rain and sun. The past weather records shown below are from weatherunderground.com [28].

Table E2: Weather data for Corvallis, OR from September, 2014, to December, 2016, which marks the span of the project [28].

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| Jan    | high | avg | low | high | avg | low | high | avg | low | high | avg | low | high | avg | low | high | avg | low | high | avg | low | high | avg | low | high | avg | low | high | avg | low | high | avg | low | high | avg | low | high | avg | low | high | avg | low | high | avg | low | high | avg | low | high | avg | low | high | avg | low | high | avg | low | high | avg | low |
|--------|------|-----|-----|------|-----|-----|------|-----|-----|------|-----|-----|------|-----|-----|------|-----|-----|------|-----|-----|------|-----|-----|------|-----|-----|------|-----|-----|------|-----|-----|------|-----|-----|------|-----|-----|------|-----|-----|------|-----|-----|------|-----|-----|------|-----|-----|------|-----|-----|------|-----|-----|------|-----|-----|------|-----|-----|------|-----|-----|
| 20     | 48   | 44  | 41  | 45   | 39  | 36  | 93   | 84  | 21   | 51   | 46  | 42  | 46   | 41  | 39  | 93   | 83  | 22   | 46   | 42  | 39  | 45   | 39  | 36  | 93   | 87  | 23   | 44   | 40  | 35  | 37   | 36  | 32  | 93   | 88  | 24   | 42   | 38  | 35  | 37   | 35  | 34  | 100  | 90  | 25   | 46   | 38  | 30  | 37   | 34  | 31  | 28   | 100 | 26   | 35   | 32  | 30  | 34   | 31  | 28  | 100  | 91  | 27   | 42   | 38  | 33  | 39   | 36  | 32  | 93   | 91  | 28   | 51   | 45  | 39  | 43   | 39  | 37  | 93   | 90  | 29   | 42   | 40  | 37  | 39   | 37  | 36  | 100  | 90  | 30   | 42   | 36  | 30  | 37   | 32  | 28  | 93   | 85  | 31   | 42   | 34  | 26  | 30   | 26  | 23  | 100  | 80  |

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<p>| Feb             | high | avg | low | high | avg | low | high | avg | low | high | avg | low | high | avg | low | high | avg | low | high | avg | low | high | avg | low | high | avg | low | high | avg | low | high | avg | low | high | avg | low | high | avg | low | high | avg | low | high | avg | low | high | avg | low | high | avg | low | high | avg |
|-----------------|------|-----|-----|------|-----|-----|------|-----|-----|------|-----|-----|------|-----|-----|------|-----|-----|------|-----|-----|------|-----|-----|------|-----|-----|------|-----|-----|------|-----|-----|------|-----|-----|------|-----|-----|------|-----|-----|------|-----|-----|------|-----|-----|------|-----|-----|------|-----|-----|------|-----|-----|------|-----|-----|------|-----|-----|
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|-----|------|-----|-----|------|-----|-----|------|-----|-----|------|-----|-----|------|-----|-----|------|-----|-----|------|-----|-----|------|-----|-----|------|-----|-----|------|-----|-----|------|-----|-----|------|-----|-----|------|-----|
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| 2   | 78   | 63  | 48  | 52   | 49  | 45  | 45   | 87  | 62  |
| 3   | 84   | 67  | 50  | 54   | 50  | 46  | 48   | 88  | 57  |
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</table>

2016 Temp. (°F)  
Dew Point (°F)  
Humidity (%)
| Dec | high | avg | low | high | avg | low | high | avg | low | high | avg | low | high | avg | low | high | avg | low | high | avg | low | high | avg | low | high | avg | low | high | avg | low | high | avg |
|-----|------|-----|-----|------|-----|-----|------|-----|-----|------|-----|-----|------|-----|-----|------|-----|-----|------|-----|-----|------|-----|-----|------|-----|-----|------|-----|-----|------|-----|-----|------|-----|-----|------|-----|
| 1   | 48   | 44  | 39  | 45   | 40  | 36  | 93   | 87  |
| 2   | 46   | 42  | 37  | 43   | 38  | 34  | 93   | 84  |
| 3   | 51   | 46  | 42  | 46   | 42  | 37  | 93   | 84  |
| 4   | 48   | 42  | 37  | 45   | 39  | 30  | 87   | 82  |
| 5   | 41   | 39  | 37  | 37   | 34  | 32  | 93   | 85  |
| 6   | 39   | 36  | 33  | 34   | 33  | 30  | 93   | 86  |
| 7   | 35   | 32  | 28  | 32   | 28  | 25  | 93   | 82  |
| 8   | 35   | 32  | 28  | 34   | 29  | 25  | 93   | 85  |
| 9   | 48   | 42  | 35  | 46   | 40  | 28  | 93   | 88  |
| 10  | 50   | 44  | 39  | 45   | 40  | 37  | 93   | 84  |
| 11  | 48   | 45  | 42  | 43   | 40  | 37  | 87   | 83  |
| 12  | 50   | 42  | 33  | 43   | 36  | 30  | 100  | 84  |
| 13  | 39   | 36  | 33  | 36   | 32  | 28  | 93   | 88  |
| 14  | 33   | 30  | 28  | 30   | 28  | 25  | 93   | 86  |
| 15  | 32   | 30  | 28  | 28   | 27  | 27  | 93   | 92  |
| 16  | 37   | 30  | 23  | 27   | 24  | 19  | 100  | 86  |
| 17  | 35   | 28  | 21  | 30   | 26  | 19  | 100  | 91  |
| 18  | 32   | 31  | 30  | 30   | 29  | 28  | 93   | 91  |
| 19  | 46   | 37  | 30  | 41   | 34  | 28  | 93   | 85  |
| 20  | 51   | 42  | 33  | 46   | 40  | 30  | 93   | 82  |
| 21  | 35   | 32  | 30  | 34   | 31  | 27  | 100  | 90  |

2016 Temp. (°F) Dew Point (°F) Humidity (%)
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<td>34</td>
<td>31</td>
<td>27</td>
<td>93</td>
<td>85</td>
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</tr>
</tbody>
</table>
The planer used for lumber preparation prior to CLT billet manufacturing was maintained by OSU graduate students and faculty. When straight blades were chipped, raised lines would appear on the planed surface. Assessment of planer chips was done qualitatively, but blades were typically replaced when 3-4 raised lines would appear on a lamination during planing. At this point, the blades were removed and sharpened by professionals. Three sets of 15 inch, high carbon steel planer blades were used in rotation to reduce planer down time during blade sharpening.

After straight blade replacement, blade straightness was validated to ensure the blades were parallel to the planer table within the lamination thickness tolerance, as specified by ANSO/APA PRG 320-2012. To replace the three straight blades, a “planer pal” tool (Planer Pal W1216A) was purchased and used to set the blades to a fixed height. This works by use of magnets to hold the tool to the planer cutter head and hold a blade at a set height above said cutter head. The blade can then be tightened into place.

Blades were checked to be parallel to table and all to a height tolerance of ±0.008 inch (±0.2 mm), which is the lamination thickness tolerance. This was done using a feeler gauge (Starrett No. 25-441) with ±0.001 inch precision attached to a magnetic base. The base was attached to the planer table and the gauge was zeroed to one end of one blade. The feeler gauge was moved to all other ends of each blade, and
if the feeler gauge read greater than .008 inches, the process was repeated. After all straight blades were replaced and checked for parallelism, all boards from the next batch of planed lumber for billet manufacturing were checked for planer tolerances.

The replacement spiral cutter head was much simpler to maintain. When a line appeared on the board, the cutting inserts could be removed, rotated 90°, and then tightened back down. Each insert is four sided, so once all four sides are chipped, the insert was replaced. The inserts were also auto indexed, so the blade height did not need to be confirmed.
7.3. Appendix C: Calibration procedure for generating an indirect control over the clamping pressure during CLT billet manufacturing.

Pressing equipment used for clamping CLT billets during the manufacturing stage included a press equipped with a pneumatic/hydraulic pump, which was connected to an air source supplied through the building which was regulated with the use of an analog pressure gauge. A correlation was made between the input air pressure from the wall and the pressing force of the press.

Panels were pressed in an OTC 55 TON ECN Hydraulic Press using a 10000 psi limit OTC pneumatic pump (model F, serial number 1706AU 228268). Since the press had no direct control over clamping pressure, a correlation between the pump’s input air pressure and the press’s clamping pressure was made. The air pressure was measured with a pressure gauge (U.S. Gauge brand) with a range of 10-200 psi and resolution of ±5 psi.

The correlation in Figure C1 was made by activating the pneumatic pump and increasing the input air pressure. The air pressure was increased from 25 psi to 45 psi in increments 5 psi, and the clamping force was recorded at each increment with ±5 ton precision using the pumps force gauge (OTC no. 9651 with range of 0-55 tons). The force gauge is standardized to 55 Ton hydraulic cylinder capacity, which has an effective cylinder area of 11 in\(^2\), according to the manufacture’s specifications [37]. Air pressure and clamping force were both measured to the nearest 5 units of measurement.
The correlation function is the Equation C1.

![Diagram: Correlation between the pneumatic pump’s input air pressure and clamping force of the CLT press with the trendline equation and R² value.](image)

**Equation C1**

\[ P_a = 1.5483 \times F_c + 15.698 \]

Where,

- \( P_a \) = the calculated air pressure [psi]
- \( F_c \) = Desired clamping force [lbs]

Equation C1 was used to calculate the input air pressures (\( P_a \)) for the designated clamping pressures in Table C1.
Table C1: Input air pressure calculations for the designated clamping pressures.

<table>
<thead>
<tr>
<th>Desired Clamping Pressures (MPa)</th>
<th>Clamping Force (psi)</th>
<th>Clamping Force (lbs)</th>
<th>Req. Air Pressure (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.69</td>
<td>100.1</td>
<td>60071</td>
<td>62.2</td>
</tr>
<tr>
<td>0.40</td>
<td>58.0</td>
<td>34824</td>
<td>42.7</td>
</tr>
<tr>
<td>0.10</td>
<td>14.5</td>
<td>8706</td>
<td>22.4</td>
</tr>
</tbody>
</table>

To get clamping pressure’s 90% confidence level, the statistical software RGui (64 bit) was used. The script for the program can be found in Appendix D. The confidence intervals for the nominal 0.10, 0.40, and 0.69 MPa clamping pressures while using the pressing correlation above can be seen in Table C1.

Table C2: Nominal clamping pressure confidence intervals for the combined uncertainty of the air pressure gauge and correlation.

<table>
<thead>
<tr>
<th>Nominal (MPa)</th>
<th>Nominal (psi)</th>
<th>90% Confidence Interval (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.10</td>
<td>14.5</td>
<td>Mean: 0.069, Lower: -0.010, Upper: 0.146</td>
</tr>
<tr>
<td>0.40</td>
<td>59</td>
<td>Mean: 0.363, Lower: 0.290, Upper: 0.435</td>
</tr>
<tr>
<td>0.69</td>
<td>100</td>
<td>Mean: 0.657, Lower: 0.586, Upper: 0.728</td>
</tr>
</tbody>
</table>

To help validate the correlation, two 20 kip load cells (Sensotec model 41/573-02) were set at locations symmetrical to the center line of the press. Equation C1 was used to calculate the input air pressures required to achieve desired clamping forces of
6, 10, 15, and 19 tons (these values were chosen due to limits of the load cells or resolution of the press gauge).

The air pressure was set to calculated levels and the press system was activated. Once the press had reached the maximum clamping forces for each calculated input air pressure, the values on the load cells were recorded.

\[ \Delta = \frac{|F_m - F_c|}{F_c} \]  

Where,

\( F_m \) = the measured force from the combined load cells [lbs]  
\( F_c \) = Desired clamping force [lbs]

The measured clamping force was the sum of the two load cell readings. To calculate the percent error of the system, Equation C2 was used. The location the two load cells were switched and the process was repeated and are referred to as trials 1 and 2. The results of the verification test can be seen in Table, which has an average error percentage to be 3.9% and a maximum error percentage equal to 5.5%.
Table C3: Correlation validation results.

<table>
<thead>
<tr>
<th>Input air pressure (±5 PSI)</th>
<th>Desired clamping force, ( F_c ) (Tons)</th>
<th>Load Cell 1 (lbs)</th>
<th>Load Cell 2 (lbs)</th>
<th>Measured, ( F_m ) (lbs)</th>
<th>Difference: Gauge &amp; Loadcell total (lbs)</th>
<th>% Error, ( \Delta )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trial 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>25</td>
<td>6</td>
<td>12000</td>
<td>5830</td>
<td>6280</td>
<td>12110</td>
<td>110</td>
</tr>
<tr>
<td>30</td>
<td>10</td>
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<td>9856</td>
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<td>972</td>
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<td>30000</td>
<td>13750</td>
<td>14660</td>
<td>28410</td>
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<td>19</td>
<td>38000</td>
<td>17750</td>
<td>18800</td>
<td>36550</td>
<td>1450</td>
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<td>Trial 2</td>
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<td>38000</td>
<td>17550</td>
<td>18515</td>
<td>36065</td>
<td>1935</td>
</tr>
</tbody>
</table>
7.4. Appendix D: RGui (64 bit) script for estimating the confidence intervals for clamping pressures

Since there was no direct control over the press system used for manufacturing hybrid CLT billets for use in the bond integrity qualifications testing, an indirect control using the input air pressure was used. A correlation between input air pressure and clamping pressure of the press was made for this control.

To gain an understanding of the uncertainty of using the indirect control, the 90% confidence levels for the correlation were found using the RGui (64 bit) statistical software using the script below.

Code notes are depicted with the # symbol.

```r
# Use Monte Carlo simulations to propagate uncertainty

#~ Correlation data ~
# th = correlation matrix
th = matrix(c(25,30,35,40,45,50,55,60,65,70,75,80,85,5,10,15,15,20,20,25,30,35
 ,40,40,45),nrow=13,ncol=2)

A=th[,1] # in PSI
B=th[,2] # in Tons

#~ Install Packages? ~
#install.packages("deming")
require(deming)

# Do total regression
out = deming(B~A)
EstCov = chol(out$var) # matrix square root of estimate variance
```
# Monte Carlo Simulation

n=1000000 # number of samples for Monte Carlo
sampleUn = 0.5*(runif(n)+runif(n)) # Sample from triangle distribution
InputUncert = cbind(15+10*sampleUn,35+10*sampleUn,55+10*sampleUn) # Calculate gauge read distribution

EstSample = matrix(rnorm(2*n),n,2)%*%EstCov # sample from joint
distribution of estimate error
slopeUn = EstSample[,2]+out$coef[2] # sample slope distribution from
regression fit
InterceptUn = EstSample[,1]+out$coef[1] # sample intercept distribution from
regression fit
ErrUn = rnorm(n)*out$sigma # sample additive error distribution from
regression fit

pnt1 = InputUncert[,1]*slopeUn+InterceptUn+ErrUn # Multiply and add
vectors to get output distribution
pnt2 = InputUncert[,2]*slopeUn+InterceptUn+ErrUn
pnt3 = InputUncert[,3]*slopeUn+InterceptUn+ErrUn

# Find 90% confidence intervals
quantile(pnt1,c(.05,.5,.95))
quantile(pnt2,c(.05,.5,.95))
quantile(pnt3,c(.05,.5,.95))

# Note: We used triangle distribution to model gauge read uncertainty
# because: a) the mode is center tick, b) there is not chance of choosing a tick
# that is farther than one tick away c) exactly between 2 ticks has probability
# 0.5, # d) for its simplicity
7.5. Appendix E: Calculating wood failure fraction of block shear specimen bond areas using image analysis.

Wood failure analysis was done by using ImageJ software for measuring quantities and the java code for deriving quantities. The ImageJ software was used to count the pixels for both wood and adhesive. The java code was used for calculating the percentage of wood failure from the pixel count.

The procedure used in ImageJ to calculate the WF percentage of the failed block shear bondlines is listed below. The steps of the process were controlled by a java script to speed up the process. There are two forms of the java script, since the PRF and PUR adhesives each use a different spectrum in the greyscale. PRF images were evaluated in the red spectrum and PUR images were evaluated in the green spectrum.

**ImageJ procedure:**

1. Open the image of interest
   1. (File > open)

2. Select bond area using Polygon tool

3. Crop image
   2. (Image > Crop)

4. Clear Outside
   3. (Edit > clear outside)

5. Put into Grayscale
   4. (Image > Type > RGB Stack)
6. Spectrum selection: greatest contrast
   5. (Scrolling right/left changes between red, blue, and green)
   6. (The best contrast for PRF and PUR were the red and blue spectrums, respectively)

7. Thresholding
   7. (Image > Adjust > Threshold)

8. Thresholding values
   9. (Record thresholding range)

9. Retrieve Histogram Data
   10. (Analysis > Histogram > No > Copy)

10. WF Calculation
   11. Paste into excel or comparable analysis software. The first column is the grey scale value and the second is the number of pixels with that value.

12. Write a function that adds the amount of pixels within the threshold range and divide by the total number of pixels (sum of column two).

**Java Script for PRF:**

This script was originally written by Warren Sept, a summer high school intern, for the use of PRF. It was later edited for use with PUR adhesive.
macro "Threshold Action Tool - C037T3f20T"{

//let user select image and open it
path = File.openDialog("Choose Image");
open(path);
//save path without .jpg
newpath = substring(path,0,lengthOf(path)-4);
//save the name of the image
title = substring(getTitle(),0,lengthOf(getTitle())-4);

//let user select the area to be analyzed
setTool("polygon");
waitForUser("Make Selection");
//save coordinates of selection points
getSelectionCoordinates(xpoints, ypoints);

//crop for easier viewing
run("Crop");
run("Clear Outside", "stack");

//optional save cropped picture
saveAs("jpeg", newpath+"-crop.jpg");

//convert to RGB stack and delete green and blue slices
run("RGB Stack");
run("Next Slice [>]");
run("Delete Slice");
run("Next Slice [>]");
run("Delete Slice");

//optional save red slice
    //saveAs("jpeg", newpath+"-red.jpg");

//finds the low point in the middle of the histogram
getHistogram(0,count,256);
min = count[150];
low=150;
for(x=100;x<200;x++){
if(count[x]<min){
    min=count[x];
    low=x;
}

//set the threshold to the low point
setThreshold(1,low);

//let the user change the threshold
run("Threshold... ");
waitForUser("Set Threshold");
//selectWindow("Threshold");
run("Close");

//make custom table
f = "[Results]";
run("New... ", "name="+f+" type=Table");
print(f,"\Headings:"+title+"\t");

//show the threshold values
getThreshold(lower,upper);
print(f,"lower\tupper");
print(f,lower+"\t"+upper);

//add up and show the pixels inside and outside the threshold
in=0;
out=0;
print(f,"in\tout");
for(x=lower;x<upper+1;x++){
    in+=count[x];
}
for(x=0;x<lower;x++){
    out+=count[x];
}
for(x=upper+1;x<256;x++){
    out+=count[x];
}
print(f,in+"\tt"+out);
//add in and out to get the total area
print(f,"area=\t"+(in+out));
//calculate and show the percent resin/wood
print(f,"%resin=\t"+(in*100)/(in+out));
print(f,"%wood=\t"+(out*100)/(in+out));

//show the selection points
print(f,"X\tY");
for(x=0;x<xpoints.length;x++){
    print(f,xpoints[x]+"\t"+ypoints[x]);
}

//show the ammount of pixels for each red value
print(f,"value\tcount");
for(x=0;x<256;x++){
    print(f,x+"\t"+count[x]);
}

//save the table as a .txt with the same name as the image
saveAs("measurements...", newpath+".txt");

//close table, threshold and image
run("Close");
run("Close");

Java Script for PUR:

//Warren Sept
//July 1, 2015

macro "Threshold Action Tool - C037T3f20T"{

//let user select image and open it
path = File.openDialog("Choose Image");
open(path);
//save path without .jpg
newpath = substring(path,0,lengthOf(path)-4);
//save the name of the image
title = substring(getTitle(),0,lengthOf(getTitle())-4);

//let user select the area to be analyzed
setTool("polygon");
waitForUser("Make Selection");
//save coordinates of selection points
getSelectionCoordinates(xpoints, ypoints);

//create results folder
parent = File.getParent(path);
if(!File.isDirectory(parent+"\Results\")) {
    File.makeDirectory(parent+"\Results\");
}

//crop for Selection
run("Crop");
run("Clear Outside", "stack");

//save cropped picture
saveAs("jpeg", parent+"\Results\"+title+-"crop.jpg");

//convert to RGB stack and delete red and blue slices
run("RGB Stack");
run("Delete Slice");
run("Next Slice []");
run("Next Slice []");
run("Delete Slice");

//optional save green slice
    //saveAs("jpeg", newpath+-"green.jpg");

//finds the low point in the middle of the histogram
getHistogram(0,count,256);
min = count[100];
low=100;
for(x=500;x<150;x++){   
    if(count[x]<min){    
        min=count[x];    
        low=x;
    }
}

//set the threshold to the high point
setThreshold(low,254);

//let the user change the threshold
run("Threshold... ");
waitForUser("Set Threshold");
//selectWindow("Threshold");
run("Close");

//make custom table
f = "[Results]";
run("New... ", "name="+f+" type=Table");
print(f,\Headings:"+title+"t");

//show the threshold values
getThreshold(lower,upper);
print(f,"lower\tupper");
print(f,lower+"\tt"+upper);

//add up and show the pixels inside and outside the threshold
in=0;
out=0;
print(f,"in\tout");
for(x=lower;x<upper+1;x++){
in+=count[x];
}
for(x=0;x<lower;x++){
out+=count[x];
}
for(x=upper+1;x<256;x++){
out+=count[x];
}
print(f,in+"\tt"+out);
//add in and out to get the total area
print(f,"area=\tt"+(in+out));

//calculate and show the percent resin/wood
print(f,"%resin=\t"+(in*100)/(in+out));
print(f,"%wood=\t"+(out*100)/(in+out));

//show the selection points
print(f,"\n\n\tX\tY");
for(x=0;x<xpoints.length;x++){
    print(f,xpoints[x]+"\t"+ypoints[x]);
}

//show the amount of pixels for each red value
print(f,"value\tcount");
for(x=0;x<255;x++){
    print(f,x+"\t"+count[x]);
}

//save the table as a .txt with the same name as the image
saveAs("measurements...", parent+"\Results\"+title+".txt");

//close table, threshold and image
run("Close");
run("Close");
}
Appendix F: Bondline delamination example images with their corresponding delamination length and percentage.

The delamination test procedure followed AITC T110-2007 test procedure, which is designed to determine the effects of accelerated cyclic exposure on the bondline of glued laminated timber specimens using vacuum-pressure-soak followed by rapid drying. For CLT qualification testing per PRG 320, AITC T110 is limited to one cycle of vacuum/pressure soak followed by one rapid drying.

Delamination was defined as any separation at the bondline that was not a result of wood failure, or was not at a wood defect location. Each bond line of each face was measured for delamination length and total bondline length [34].

Delamination length for each bondline was measured directly after the vacuum-pressure-soak and drying cycle to prevent delamination cracks closing from moisture uptake from the air or cooling of the block.

Analysis of delamination was dividing the total delamination length by the total bondline length to get the percentage of delamination. ANSI A190.1-2007, referred by PRG 320, prescribes a maximum delamination for any one specimen cannot exceed 5%. If this happens, the sample fails the bond integrity qualification test.

Images below show bondline delamination with recorded length and corresponding delamination percentage for the entire specimen (eight bondlines of 76mm each). For a specimen to pass, each bondline must have an average delamination length of \( \leq 3.8 \text{mm} \).
Red indicators are placed in the images to help point out areas of delamination, but are not to scale with original measurements. A dashed line represents sections with both delamination and wood failure.

DDL69U1-D1-1B = 14mm (2.3%) of total specimen delamination %

DHL69F1-D3-1B = 21mm (3.4%) of total specimen delamination

DDL40U2-D3-1B = 25mm (4.1%) of total specimen delamination
DDL40U3-D2-4T = 34mm (5.6%) of total specimen delamination

PPH69F3-D3-3B = 38mm (6.25%) of total specimen delamination

DDL69U3-D3-3B = 40mm (6.6%) of specimen delamination
DDL69U2-D3-2B = 57mm (9.4%) of total specimen delamination

DDL69U2-D1-3B = 69mm (11.3%) of total specimen delamination

DDL10U1-D3-1T = 76mm (12.5%) of the total specimen delamination