AN ABSTRACT OF THE DISSERTATION OF

Sina Jahedi for the degree of Doctor of Philosophy in Wood Science presented on March 07, 2022.

Title: Defining Project-Specific Custom CLT Grade Utilizing Low-Value Ponderosa Pine Lumber from Logs Harvested in SW Oregon and Northern California Forest Restoration Programs.

Abstract approved:

______________________________________________________

Lech Muszynski

Restoration programs effectively prevent or mitigate wildfires and pest outbreaks in the forest lands. The most common approach is to selectively harvest smaller and dead trees in order to preserve larger and superior trees. Ponderosa pine, Pinus ponderosa, (PP) lumber is one of the common species harvested from restoration programs in Southern Oregon and Northern California. This lumber is not considered as structural material and have a limited market in the US because it is obtained from small diameter trees and contains substantial amounts of juvenile wood, knots, wane, warp, and twist. USDA Forest Service is seeking for a value-added market for the lumber to offset the high costs of these programs.

Engineered wood products, such as Cross-Laminated Timber (CLT), are expected to provide such market. CLT is a massive, engineered wood panel consisting of three or more orthogonal plies of lumber bonded with an adhesive. The overall goal of this project was to assess the feasibility of structural CLT panels produced entirely by low-value PP lumber obtained from forest restoration programs. The proposed end-
use application for such product is low-rise modular construction which potentially provides a meaningful and consistent outlet for substantial volumes of forest restoration lumber. While this PhD work was focused on determination of mechanical characteristics of custom PP CLT layups, a parallel PhD study was aimed at utilizing the product to design a prototype modular building.

The specific objectives of the presented study were to:

- Determine the potential for utilizing Ponderosa pine from restoration programs in custom CLT layups.
- Determine the bonding performance and allowable levels of blue stain in CLT panels meeting custom grade specs.
- Define a custom CLT grade(s) meeting engineering requirements of a target modular design and determine the effect of fabrication scale on the mechanical performance.

The moduli of elasticity (MOE) of a sample restoration program PP lumber were measured and compared to previous studies and published values for commercially harvested PP as reflected in the NDS Western Woods (WW) species group. While the characteristic MOE values of visually graded No. 1 and 2. restoration programs lumber were lower than respective grades for NDS WW, the characteristic MOE values of all individual groups exceeded the design value of NDS WW grade No. 3. Therefore, the design values published for WW grade No. 3 were selected as provisional conservative representation of the restoration program PP lumber.

Following PRG-320, bond integrity tests, including block shear and cyclic delamination, were conducted on specimens bonded with melamine formaldehyde (MF) adhesive. The aim was to separate the effect of adhesive compatibility from other fabrication factors affecting bonding performance by testing specimens fabricated in three ways: 1) pilot-plant scale, 2) full-scale industrial CLT plant; 3) standalone small blocks with high contents of blue stain and juvenile wood but no bridging between neighboring laminations. All groups of the block shear specimens passed the PRG-320 criterion. All specimens that were fabricated in small blocks met the delamination criterion, demonstrating that heavy presence of blue-stain and
juvenile wood does not impact the compatibility of the MF adhesive system with PP. Specimens obtained from pilot-plant and industrial prototypes had high delaminations which were propagated from interlaminar gaps observed in the specimens prior to the test. The cause of interlaminar gaps were tracked back to thickness variation and inconsistent clamping pressure in the pilot-plant.

The shear analogy method was integrated in a computer application to design a custom PP CLT layup meeting the minimum design characteristic requirements derived for the target modular building. The mechanical characteristics of the layup was experimentally assessed by conducting bending tests on pilot-plant and industrial prototype panels, made with random assignment of grades No. 1, 2, 3 and ungraded laminations to all layers. Third-point and three-point flatwise bending tests, as per ASTM D198 standard, were conducted to derive effective moment capacity, stiffness, and shear capacity. An optical system was used to measure the average shear strain on the depth of the beams and calculate effective shear rigidity. The results showed that all experimentally derived design characteristics exceeded the building requirements. Compared to the values predicted from the shear analogy method, prototype CLT layups had higher effective moment capacity, stiffness, and shear rigidity, but lower shear capacity which was potentially caused by interlaminar gaps.

In conclusion, the average MOE of grade No.2, No.3, and ungraded Ponderosa pine lumber obtained from restoration programs had no significant difference. A proof of concept has been provided, showing it is possible to design custom layups using Ponderosa pine lumber in all layers to meet the requirements of a certain class of low-rise modular building. A procedure has been proposed allowing successful separation of adhesive compatibility from other fabrication factors, eliminating adhesive compatibility as a potential cause of the delaminations. MF adhesive system provides sufficient bonding performance with PP lumber harvested from restoration programs. A combination of fabrication factors that were only present in production of prototype panels led to development of interlaminar gaps and large delaminations in some specimens. Provided that these technological issues are identified and eliminated, it was shown that Ponderosa pine lumber obtained from logs harvested in SW Oregon and Northern California forest restoration programs can be utilized in project-specific
CLT grades for a certain type of low-rise building. The out of plane properties were not studied. No significant difference was found between the performance of pilot-plant and industrial prototypes.
Defining Project-Specific Custom CLT Grade Utilizing Low-Value Ponderosa Pine Lumber from Logs Harvested in SW Oregon and Northern California Forest Restoration Programs

by
Sina Jahedi

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Dean of the Graduate School

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Sina Jahedi, Author
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Dr. Lech Muszynski and Dr. Mariapaola Riggio collaborated on the experimental design, reviewing, and editing of each chapter. Sujit Bhandari collaborated on determination of design requirements for chapter 2 and 4. Benjamin Brice Blengino assisted with data collection and preliminary analysis in chapter 2.
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General Introduction
1.1 Motivation

Substantial number of logs harvested from restoration programs in Southern Oregon and Northern California are considered as low-value material since they are thin in diameter and a considerable amount of them contains juvenile wood and biotic attack by blue-stain fungi. In addition, lumber obtained from these logs exhibit large amounts of wane (due to conversion of small diameter logs), as well as distortions such as bow and twist (due to the higher longitudinal shrinkage of the juvenile wood). Considering that restoration programs are essential for wildfire prevention, the motivation of this study was to offset the high costs of these operations by finding a value-added market for the material harvested. Particularly, this study aimed to assess the potential of using restoration program harvested Ponderosa pine (PP) for fabrication of structural cross-laminated timber (CLT) for a specific type of low-rise modular buildings. To achieve this goal, non-destructive tests were performed on the restoration program PP to determine mechanical properties of the lumber, numerical methods were followed to design a suitable layup, and experimental tests were conducted to assess the bond and mechanical performance of PP CLT panels.

1.2 Background

1.2.1 Restoration Programs

National forest restoration programs aim to reduce wildfire spread rate by selectively removing small diameter trees to preserve larger and superior trees (Johnston et al. 2021). The most common approach is “thinning from below” where the lower crown classes or canopy layers are removed in order to preserve upper crown classes or layers (Powell 2013). In this manner, when a fire starts, only the plants closer to the ground would burn and the fire doesn’t reach the branches of taller trees, Figure 1-1. Restoration programs in Southern Oregon and Northern California select for cutting trees smaller than 22 inches in diameter (Operator at Collins Co. 2018). Many of the harvested trees are either dead or diseased, thus representing potential fuel for wildfires and source of pest outbreaks.
The thinning operations are costly due to accessibility issues and requirement for large machinery. As an example, the thinning program in Lakeview, OR, showed in Figure 1-2 uses a number of different machinery including: a large tree cutter capable of picking up and moving full trees, a debranching machine, a skidder for picking up underbrush and moving cut logs, and trucks to load and move the logs to sawmills. 8 operations run at a time, with 4-5 workers per operation, ultimately producing 1-2 million board feet of lumber per month. Their forests consist of 60% government owned and 40% private land, each with growths of White Fir (*Abies concolor*) and Ponderosa Pine (*Pinus ponderosa*, referred as PP in this dissertation) (Operator at Collins Co. 2018). The thinning operation shall recur every ten years on a stewardship area.
1.2.2 Characteristics of Lumber Generated from Restoration Programs

The timber harvested from thinning operations is of low value compared to commercially harvested lumber. This is due to the fact that the material is acquired from smaller diameter trees, having high contents of juvenile wood, which has higher microfibril angle (MFA) and thinner cell walls, resulting in higher longitudinal shrinkage, lower specific gravity, and lower strength compared to mature wood (Kretschmann 2010).

Another fact reducing the value even further is that some of the harvested trees are dead and prone to fungal attacks. Ascomycetes fungi cause blue stain in wood (Byrne et al. 2005) which is abundant among the PP lumber harvested from Southern Oregon and Northern California. Although blue stain is considered to have minimal effects on wood mechanical properties (Chapman and Scheffer 1940), some standards, e.g. for utility poles and cross arms, prohibit the use of blue-stained material (ANSI 2015a, b).
Furthermore, lumber obtained from small diameter trees contains substantial presence of knots, wane, warp, and twist, which results in lower fractions of the higher structural grades compared to the yield from commercial stands. In the section 2 of this dissertation the characteristics of restoration harvested PP is discussed in more details.

1.2.3 Current Schemes for Utilization

The market for PP lumber harvested in restoration programs is extremely limited in the Pacific NW. Substantial portion of the material harvested in Southern Oregon and Northern California does not meet the requirements of structural grade lumber and is turned into chips to be used as biofuel or for fabrication of hardboards and particleboards (Smith 2021). Specifically, contractors are hesitant in purchasing blue stain PP for structural purposes, and sawmills typically sell this material for a lower price to the nearby artists and carpenters (Operator at Collins Co. 2018). As an example, blue stain PP lumber was used as decorative paneling for the interior of a bowling alley in Lakeview, OR.

The high costs of restoration programs need to be offset in order to increase the pace and space of restoration program further. Previous study at Oregon State University suggested that production of cross-laminated lumber (CLT) by restoration program PP can potentially provide a value-added market (Lawrence 2017a). CLT is a massive, engineered wood panel consisting of three or more orthogonally arranged plies of lumber bonded with an adhesive. Experimental studies on hybrid Lodgepole pine–Douglas fir (Larkin 2017) and hybrid PP–Douglas fir (Lawrence 2017b) CLT panels demonstrated that the products provide sufficient mechanical performance for structural use. Another study showed that about 28% of restoration program PP lumber can be used for production of a new PP glulam beam combination with better performance compared to all PP L3-grade combinations (Hernandez et al. 2005). Lastly, a small-scale CLT manufacturer in Colorado has started fabricating non-structural restoration program PP panels since 2018, currently most of the products
include furniture but the prospect is to produce structural panels in the near future (Timber Age 2018).

1.2.4 Challenges and Research Gaps

Previous empirical studies demonstrated that lumber obtained from small diameter trees has reduced mechanical properties compared to commercially harvested lumber, mostly due to high presence of juvenile wood (Kretschmann and Bendtsen 1992; Erikson et al. 2000; Vaughan et al. 2021). However, none of those studies quantified the impact of juvenile wood on the mechanical properties of Pacific PP, which is the sub-species grown in Southern Oregon and Northern California.

Additionally, presence of juvenile wood in lumber is not among considered features for visual grading. Therefore, the reduction in mechanical properties due to presence of juvenile wood is practically ignored in this grading system. Before this study, it was uncertain whether the properties published for commercially harvested PP can be applied to the restoration program material.

Juvenile wood has higher shrinkage compared to mature wood (FPL 2010). Few studies have analyzed the impact of juvenile wood’s differential shrinkage on the quality of laminated products, due to the possible occurrence of induced stresses on the bonding surface (Raftery et al. 2008). Additionally, the impact of blue stain on bond integrity of all common types of adhesives have not been studied yet, including melamine formaldehyde (MF), which is one of the common adhesive systems in the North-West United States.

Grade No. 3 PP lumber can only be used in core laminations of the CLT grades that are prescribed by the North American standard. This of course limits the utilization considering the fact that “grade No. 3 and below” form more than half of the restoration program material. There was a gap in knowledge whether the entirety of the material can be used in all laminations of CLT panels without the need to sort based on grades. The prerequisite to answer this question was to determine if the
entirety of the lumber can be regarded as one class of material, and to find a suitable set of mechanical properties for the whole group.

1.3 Hypothesis

The hypothesis was that it is possible to fabricate structural CLT panels entirely from PP lumber harvested in restoration programs in Southern Oregon and Northern California. The goal was to use the lumber in all layers of the panel without the need to sort it according to its grade, thus reducing the production costs.

To justify economic benefit for CLT panels, the target structural application for this product should have potential for high volume utilization, thus providing a meaningful and consistent outlet for forest restoration lumber. Our hypothesis is that low-rise modular structures may provide such an outlet. A modular building is composed of repeating modules “constructed with standardized units or dimensions for flexibility and variety in use” (Merriam-Webster 2021) that are built off-site, delivered and assembled on-site. The repeatability of modular building components allows to produce a large number of similar units for a particular end-use. While industry identified a competitive advantage for standard CLT in mid- to high-rise buildings (Brandner et al. 2016), PP CLT could target an alternative market segment, i.e., buildings with a lower structural demand, such as low-rise temporary buildings.

1.4 CLT as a Structural Material

CLT is a massive, engineered wood panel consisting of three or more orthogonally arranged plies of lumber bonded with an adhesive which is typically used for structural wall, floor, and roof assemblies. CLT, has orthogonal properties, meaning that unlike homogenous materials, the properties vary in perpendicular directions. These are commonly referred to as the major strength direction (parallel to the outmost plies) and the minor strength direction (perpendicular to the outmost plies). CLT was first introduced in Austria and Germany in the early 1990s (Mohammad et al. 2012). While the majority of the manufacturers are located in Europe, the
technology has been adopted in other regions as well, such as Canada, the US, Japan, and New Zealand (Muszynski et al. 2017). The first company producing structural CLT panels in the US is DR Johnson, Redding OR, which started production in 2015, followed by Smartlam, Whitefish MT, in 2016. Since then, several other manufacturers have emerged in the country. Some of them, such as Vaagen Timbers, Colville WA, and Timber Age, Durango CO, have shown interest in utilizing restoration harvested PP (Vaagen 2017; Timber Age 2018).

Wood is a renewable material and provides higher strength-to-weight ratio compared to steel and concrete. The layered composition of CLT helps with spreading the impact of individual defects on the whole panel, resulting in a more homogenized product, with more predictable mechanical performance (Cherry et al. 2019). Additionally, the crosswise orientation of the plies gives dimensional stability to the panel, which minimizes tolerances and makes it a suitable material for prefabrication.

1.5 The Standard for CLT in North America

The first edition of the North American ‘Standard for Performance-Rated CLT’, ANSI/APA PRG-320, was developed in 2011. This standard specifies the qualification requirements for laminations, performance of panel, and quality assurance procedures. The standard mandates that all the lumber used for laminations must be qualified for a structural grade. The longitudinal layers must be 1200f-1.2E machine stress rated (MSR) or visual grade No. 2 or higher, and the grade of laminations in the transverse layers must be a minimum of visual grade No. 3. The standard provides a list of predefined layups named as “basic CLT grades and layups”. PRG-320 also permits to use custom layups, if the product meets the required performance qualifications, summarized in Table 1-1. Therefore, theoretically it is allowed to use alternative species and grades of lumber, as well as arbitrary thickness and number of plies in longitudinal and transverse directions.
Table 1-1. Summary of performance tests specified by PRG-320 2019.

<table>
<thead>
<tr>
<th>Test Name</th>
<th>Standard Adopted From</th>
<th>Standard’s Section</th>
<th>Span/Depth Ratio</th>
<th>Destructive?</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bond Integrity Tests</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cyclic Delamination</td>
<td>AITC-T110</td>
<td>1-7</td>
<td>N/A</td>
<td>YES</td>
</tr>
<tr>
<td>Block Shear</td>
<td>AITC-T107</td>
<td>1-8</td>
<td>N/A</td>
<td>YES</td>
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<tr>
<td><strong>Structural Performance Tests</strong></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flatwise Bending</td>
<td>ASTM D198</td>
<td>4-12</td>
<td>Major: 30</td>
<td>YES</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Minor: 18</td>
<td></td>
</tr>
<tr>
<td>Flatwise Shear</td>
<td>ASTM D198</td>
<td>4-12</td>
<td>Major: 5 to 6</td>
<td>YES</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Minor: 5 to 6</td>
<td></td>
</tr>
<tr>
<td>Flatwise Stiffness</td>
<td>ASTM D198</td>
<td>45-52</td>
<td>4 various spans</td>
<td>NO</td>
</tr>
<tr>
<td>Volume, Creep, load Duration Effects</td>
<td>ASTM D5456</td>
<td>7.4.1</td>
<td>Major: -</td>
<td>YES</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7.4.2</td>
<td>Minor: -</td>
<td></td>
</tr>
<tr>
<td>Edgewise Bending</td>
<td>ASTM D198</td>
<td>4-12</td>
<td>Major: 18</td>
<td>YES</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Minor: 18</td>
<td></td>
</tr>
<tr>
<td>Edgewise Shear</td>
<td>ASTM D5456</td>
<td>Annex A3</td>
<td>Major: -</td>
<td>YES</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Minor: -</td>
<td></td>
</tr>
<tr>
<td>Edgewise Stiffness</td>
<td>ASTM D198</td>
<td>45-52</td>
<td>4 various spans</td>
<td>NO</td>
</tr>
</tbody>
</table>

1.5.1.1 Comparison with EN 16351 (European standard)

Similar to PRG-320, the European standard for CLT, EN 16351, strictly prohibits the utilization of ungraded timber in laminations, however, there are no minimum grade requirements for transverse and longitudinal layers. Another major difference in the material selection is that EN 16351 restricts the species to a specific list mentioned in the standard.

The performance qualification tests included in EN 16351 also have some differences compared to PRG-320. The main difference in the structural performance tests is that, in addition to third-point bending tests, EN 16351 provides an alternative testing method to derive shear strength and stiffness when the CLT is subjected to in-plane compression loads parallel to the major direction of the panel.
The most important differences are related to the requirements for bond integrity tests. Firstly, EN 16351 gives the option to perform either cyclic delamination or block shear tests; with an emphasis on block shear as a reference method. EN 16351 permits testing on cylindrical specimens as well as quadratic cuts while PRG-320 only allows quadratic cuts. The pass and fail criteria are different as well. EN 16351 requires a maximum of 10% delamination in each specimen while this number is 5% in PRG-320. Therefore, it can be expected that meeting the PRG-320 bond integrity criteria will be more challenging compared to EN16351. As discussed in Section 3, satisfying the PRG-320 delamination criterion is a persistent challenge in qualification of new CLT layups.

Moreover, the two standards have different approaches towards qualification of panels in block shear test. PRG-320 relies on wood failure (WF) assessments. WF is expressed as percentage and derived based on the ratio of the area with wood fiber remaining at the bond line to the total bonding area involved in the test. PRG-320 requires a minimum of average 80% WF in all specimens. On the other hand, EN 16351 requires a characteristic shear strength more than 1.25 MPa in all specimens, and at least 1 MPa in each glue line.

1.6 Modular Buildings

Unlike traditional building materials such as cast-in-place concrete or light frame timber, CLT is a prefabricated product. As defined by the Modular Building Institute (MBI), prefabrication involves the production of building assemblies and/or components in an off-site plant and on-site delivery for installation (MBI 2010). The entirety of CLT production steps, from processing the lumber to layup assembly and cutting openings, happen in a manufacturing plant off-site. The product is typically ready to be installed when delivered on-site.

Prefabrication can reduce material waste, labor work, and building erection time, and since the majority of tasks are performed in an off-site environment, it can improve safety and overall quality while reducing costs (Gibb 2001). Moreover,
standardization of dimensions and designs results in quality improvement and lower costs (Hermes 2015). Such benefits become more rewarding when larger number of modules are produced in a plant. In that case, the manufacturer can take advantage of automated serial production to achieve more efficiency.

Prefabrication comes in a variety of scales, from small components to volumetric 3D units. Modular construction reduces the total work time on-site and can be a solution for building in environments with extreme seasons that have limited on-site operation time. Additionally, modular construction reduces the pollution on-site, enhances safety, and minimizes the waste (Gasparri et al. 2015). By the help of highly developed shipping companies, modern modular construction makes it possible to order and add new housing stocks and accessory dwelling units to buildings within a few days (McKeough 2018). Modular construction can be faster and have the potential to reduce overall energy consumption when compared to traditional on-site construction (Kamali et al. 2019).

1.6.1.1 CLT modules

The use of CLT in modular construction is feasible since CLT gives the possibility to achieve high levels of prefabrication off-site, and delivering the building components as panelized or volumetric modules to site for assembly (Huß et al. 2019). Computer Numerical Control (CNC) routers are used to cut the openings for utilities, doors and windows to reduce the overall assembly time onsite. The lumber used in CLT can be finger-jointed to form long laminations, therefore CLT systems theoretically permit large unsupported areas that exceeds the length of individual boards in traditional wood-frame systems and gives the flexibility to designers to use the area for multiple purposes. For example, an open classroom module in a school can be divided into smaller offices or combined with adjacent modules to form a meeting room. The length of CLT panels is mostly limited by the size of the transportation vehicle.

The scale of modularity has a significant impact on the transportability of the modules. Multiple panelized units can stack on top of each other to efficiently use the cargo space of transportation vehicles, while volumetric modules contain void spaces
which results in consuming more space compared to 2D modules. Moreover, large volumetric modules can cause logistic issues such as storage complications, either on the factory plant or the construction site.

1.7 General goal and objectives

This PhD work is part of a larger project, whose general goal is to demonstrate the feasibility of utilizing restoration harvested PP lumber in custom CLT panels for a specific class of low-rise modular buildings. The project assesses such feasibility on two different levels, material level and structure level. This thesis is concerned with the material level, expanding from the properties of lumber to the bonding quality, and the mechanical characteristics of CLT panels.

1.7.1 Specific objectives of this thesis

- Determine the potential for utilizing Ponderosa pine from restoration programs in custom CLT layups by:
  - Determining the distribution of the modulus of elasticity (MOE) of lumber harvested from restoration programs in Southern Oregon and Northern California
  - Estimating the design values of restoration harvested PP for designing custom CLT layups.

- Determine the bonding performance and allowable levels of blue stain in CLT panels meeting custom grade specs by:
  - Assessing bonding integrity of PP CLT through cyclic delamination and block shear tests.
  - Developing a methodology to separate the effects of fabrication factors from adhesive compatibility.

- Define a custom CLT grade(s) meeting engineering requirements of a target modular design and determine the effect of fabrication scale on the mechanical performance, by:
Designing a custom layup CLT optimized for the target structural design.

Experimentally assess mechanical performance of the designed CLT layup, testing CLT prototypes fabricated in laboratory and industrial settings.

1.8 General statement of approach

The general approach of the overall project was to use an iterative procedure to optimize both, the CLT layup and the structural engineering design of the structure, for the most efficient solution. Therefore, the project is organized in corresponding parallel iterative workflows. The simplified flowchart of the project is shown in Figure 1-3.

The material level (the focus of this PhD work) analysis is aimed at determination of mechanical properties of custom layups made by low-value PP CLT obtained from forest restoration programs. These properties are commonly predicted from the mechanical properties of the lamstock, therefore, selected properties of restoration program PP had to be determined. If there was an acceptable match between the measured characteristics of low-value PP CLT generated by forest restoration programs and the published values for commercially harvested lumber, the latter could be used in designing the custom PP layups. Otherwise, the full set of mechanical properties of restoration harvested PP lumber had to be determined. The procedure and outcomes of this part of the project are summarized in section 2.

Having the properties of restoration program PP, numerical methods were employed to design custom CLT layups that met the requirements of the structural design. This procedure and results are summarized in Section 4.3.1. The design characteristics of the layup were compared with the empirically determined values that were determined through a series of mechanical performance tests, as described in Section 4.4.
1.9 Structure of this thesis

The outcomes of this PhD work have been reported in three journal manuscripts. This dissertation is composed of an introduction (this section), three submitted journal manuscripts edited in the OSU’s dissertation format (sections 2-4), general discussions (section 5), overview of outcomes (section 6), and appendices. Below is the list of manuscripts included in this dissertation:
1.9.1 List of manuscripts

**First Manuscript:** “MOE Distribution in Visually Graded Ponderosa Pine Lumber Harvested from Restoration Programs in Southern Oregon and Northern California”. Journal of Wood and Fiber Science.

Co-authored by: Sina Jahedi, Lech Muszynski, Mariapaola Riggio, Benjamin Brice Blengino, Sujit Bhandari.

Status: Accepted, Winter 2022.


Co-authored by: Sina Jahedi, Lech Muszynski, Mariapaola Riggio, Sujit Bhandari.


**Third Manuscript:** “Mechanical Characteristics of Custom CLT Layups Laminated by Ponderosa Pine Harvested from Restoration Programs”. Journal of Wood and Fiber Science.

Co-authored by: Sina Jahedi, Lech Muszynski, Mariapaola Riggio, Sujit Bhandari.

MOE Distribution in Visually Graded Ponderosa Pine Lumber Harvested from Restoration Programs in Southern Oregon and Northern California

Accepted by the Journal of Wood Fiber and Science (Accepted Winter 2022).

Co-authored by: Sina Jahedi, Lech Muszynski, Mariapaola Riggio, Benjamin Brice Blengino, Sujit Bhandari.
2.1 Abstract

Every year, restoration programs in Southern Oregon and Northern California produce large amounts of low-value Ponderosa pine, Pinus Ponderosa, (PP) lumber. This material has a limited market in the US. Engineered wood products, such as CLT and glulam, are expected to provide a value-added market to offset the high costs of restoration programs. However, restoration program lumber has larger amounts of juvenile wood and visual grades are reported to show lower mechanical properties compared to commercially harvested material, on which the National Design Specification (NDS) design values are based. This research addresses a knowledge gap on the impact of juvenile wood and visual strength-affecting characteristics on the mechanical performance of PP lumber generated in the region of interest. The purpose of this study was to assess this impact based on dynamically measured moduli of elasticity (MOE) of samples of visually graded and ungraded restoration program PP lumber. The material used in this study was intended for fabrication of CLT for another project, hence it could not be used for destructive tests to measure modulus of rupture (MOR). The results were compared to previous studies and published values for commercially harvested PP as reflected in the NDS Western Woods (WW) species group. The results show that characteristic MOE values of visual grades No. 1 and 2. of PP from restoration programs were lower than respective design values for NDS WW group. However, the mean MOE values of all groups considered individually as well as pooled together were higher than NDS WW grade No. 3. MOE distributions for all groups, except for the visual grade No. 1, were remarkably similar. The average MOE of PP harvested in Southern Oregon and Northern California were higher than those reported for Columbia PP harvested in North Idaho.
2.2 Introduction

The forest lands in Western United States are prone to catastrophic wildfires and pest outbreaks. Restoration programs are implemented to prevent or mitigate such events. USDA Forest Service is seeking value-added markets for logs harvested from thinning operations to offset the high costs of these programs. While utilization in structural engineered products have been proposed (Hernandez et al. 2005; Larkin 2017; Lawrence 2017a, b), most such products require lumber graded for structural uses. There are two common lumber grading systems used in the US (Entsminger et al. 2020). The first is visual grading, where the grade is assigned based on the characteristics that are visible to the naked eye, e.g., size and location of knots, grain angle, wane, etc. This task is either done by a trained lumber grader or an automated scanning system. The second system is machine grading which includes machine stress rated (MSR) and machine evaluated lumber (MEL). For either machine grading system, a property of the material, commonly moduli of elasticity (MOE) or density, is measured as a predictor of other properties of the material, in combination with some visual limiting criteria, e.g., rejecting pieces with large edge knots (Entsminger et al. 2020). In addition to machines that bend lumber to measure stiffness, other machines use dynamic measurements, including transverse vibration to measure stiffness from the fundamental frequency of the flatwise vibration of a piece of lumber supported at the ends.

The most common approach for restoration programs is “thinning from below”, meaning that the lower crown classes or canopy layers are harvested in order to preserve upper crown classes or layers (Powell 2013). Pacific Northwest restoration programs consist of removing trees smaller than 0.5 m (22 in.) in diameter as well as dead trees (Smith 2021). The lumber obtained from these small diameter trees contains substantial presence of knots, wane, warp, and twist, which results in lower fractions of the higher structural grades, compared to the yield from commercial stands (Erikson et al. 2000; Hernandez et al. 2005; Smith 2021).
One of the species harvested in forest restoration operations in substantial quantities is Ponderosa pine, *Pinus ponderosa*, (abbreviated as PP in this paper) (Shinneman et al. 2016). Commercially harvested PP is listed among structural softwoods in the National Design Specification (NDS) supplement handbook (American Wood Council 2018). Substantial portion of the material harvested in Southern Oregon and Northern California does not meet the requirements of structural grade lumber and is turned into chips to be used as biofuel or for fabrication of hardboards and particleboards (Smith 2021). A comparison of visual grade yield of PP in typical restoration programs to commercial harvest is presented in Table 2-1. One of the main causes of reduced mechanical properties in small diameter logs is the high amount of juvenile wood, which has higher microfibril angle (MFA) and thinner cell walls, resulting in higher longitudinal shrinkage, lower specific gravity, and lower strength compared to mature wood (FPL 2010). The transition from juvenile wood to mature wood is gradual (Moore and Cown 2017), and it is not easy to determine the proportion of juvenile wood content in individual pieces of lumber by macroscopic visual clues. Currently, the presence of juvenile wood is not among grade-defining criteria in visual grading systems (WWPA 2017); hence theoretically the effect of juvenile wood on the design characteristics of graded lumber is not considered.

The characteristic values of MOE and modulus of rupture (MOR) of commercially harvested PP lumber were determined as a part of in-grade testing programs (Green and Evans 1987). This data was collected from about 80 specimens for each grade obtained from various mills around the country. No information could be found on specific locations the specimens were obtained from. Also, National Design Specification (NDS) supplement handbook provides the design values of commercially harvested PP lumber grouped with similar species as Western Woods (WW). The design values for the whole group were derived based on the weakest species for that specific property. Applying WW design values or in-grade data to restoration program PP lumber that contains a high proportion of juvenile wood is likely to result in overestimating mechanical properties. The major design values used for engineering purposes include MOE, bending strength ($F_b$), tension strength
parallel to grain ($F_t$), shear strength parallel to grain ($F_v$), and compression perpendicular to grain ($F_c\perp$). Although among these properties only MOE can be measured non-destructively, it is commonly accepted that there are linear correlations between MOE and other properties (Green and Kretschmann 1991). As per ASTM D2915, the sample mean is used for deflection-related design values, while a 5th percentile tolerance limit is considered for derivation of strength-related design values.

A study on PP lumber obtained from restoration programs in Arizona showed that MOE of straight grained small clear specimens (SCS) increases with cambial age, which is an indication of the amount of juvenile wood present in the material (Vaughan et al. 2021). Detrimental effects of juvenile wood on material mechanical properties are confirmed for other pine species. A study on Loblolly pine lumber with high content of juvenile wood showed that about 20% of the material did not conform to the design values (MOE and ultimate tensile stress) of the assigned visual grades in NDS (Kretschmann and Bendtsen 1992). Another study collected data on 2x4 PP lumber harvested from restoration programs in North Idaho (Erikson et al. 2000) and the results showed that PP lumber from thinning operations visually graded as No. 2 had lower MOE compared to the data published for that grade of commercially harvested PP. The sub-species (Pinus ponderosa subsp. ponderosa, Columbia ponderosa pine) studied by Erikson et al. 2000 is different from Pacific PP trees growing in West Oregon and Northern California (Pinus ponderosa subsp. critchfieldiana Callaham, subsp. nov., Pacific ponderosa pine) investigated in this study (Callaham 2013). However, regardless of the potential differences between sub-species, there seems to be mounting evidence that the design values established for commercially harvested Ponderosa pine may overestimate the actual properties of the lumber obtained from forest restoration thinning. The magnitude of the effect for PP lumber generated in the region of interest is the research gap addressed partially in this study.

A study on utilization of thinning program PP lumber (Hernandez et al. 2005) showed that about 28% of the material can be used to produce a new PP glulam beam
combination better than all PP L3-grade combinations published in the standards. The authors of this study reported that the major factors for rejection of lumber were wane and skip. A study conducted at Oregon State University suggested that lumber harvested in restoration programs in the Pacific Northwest could also be used for production of cross-laminated timber (CLT), adding to the diversity and resilience of the current schemes of utilization (Lawrence 2017a). CLT is a massive, engineered wood panel consisting of three or more orthogonally arranged plies of lumber bonded with an adhesive. ANSI APA PRG-320 (ANSI/APA 2019) specifies the requirements for fabrication, performance, and quality assurance of CLT panels in North America. Experimental studies (Larkin 2017; Lawrence 2017b) demonstrated that acceptable structural performance may be achieved in hybrid CLT layups including low-value PP lumber in the cores, however both studies failed to meet the resistance to cyclic delamination criteria. An example of the interest in using PP in construction may be a small-scale CLT manufacturer in Colorado fabricating non-structural restoration program PP panels since 2018, with the prospect to produce structural panels in the near future (Timber Age 2018).

Using restoration program PP lumber in all laminations of CLT is intended to maximize the utilization of the material in the value-added structural product. However, in order to predict the design properties of such layups, the design values of PP lumber generated in restoration program thinnings in the Pacific Northwest must be known first. The necessary step towards structural utilization of this material is collecting representative data on the properties of the lumber. The objective of this study was to determine the distribution of the MOE in visually graded and ungraded PP lumber harvested from restoration programs in Southern Oregon and Northern California. This study is part of a broader project aimed at utilizing ungraded restoration program PP lumber in all laminations of structural CLT. The target use of the proposed CLT layup is in low-rise modular construction, identified as a potential market for such large outlet of restoration program lumber (Bhandari et al. 2020).

**Limitation:** The PP lumber obtained for this study was intended for fabrication of CLT, performance tests on CLT elements, and construction of a demonstration CLT
unit in parallel projects conducted at the Oregon State University. This precluded destructive test procedures, like determination of MOR. Therefore, in this study, only the MOE and specific gravity distributions, which could be measured non-destructively, were determined and used for comparisons and analysis.

2.3 Materials and Methods

While the common species harvested in Southern Oregon and Northern California restoration operations include White Fir (*Abies concolor*), and PP, only PP was the focus of this project. The lumber for this project was obtained from “thinning from below” harvest, aimed at preserving the healthy trees with a diameter larger than 560 mm. The material was harvested, sawn to 2x6 nominal dimension lumber (actual dimension 38 mm by 152 mm), kiln dried to 19% moisture content (MC), and visually graded by Collins Co. (Lakeview, OR). The length of the lumber was either 2.44, 3.05, 3.66, or 4.88 m (8, 10, 12, or 16 foot).

Out of the 18 units of PP lumber donated for the fabrication of prototype CLT layups for a parallel project conducted at OSU, seven units were randomly selected for non-destructive testing. A total of 810 pieces was obtained from the units, of which 84% were visually graded by the lumber company based on the standard (WWPA 2017) as following: No. 1 (2%), No. 2 (48%), and No. 3 (34%), while the rest (16%) remained ungraded (last row of Table 2-1). The ungraded lumber was mostly blue-stained pieces acquired from dead trees. Although this portion of the material potentially could be visually graded, there is almost no demand for blue-stain lumber in the region, therefore, it is typically converted into chips.

Upon the arrival at OSU, the material was stored outdoors in the original tight units without any spacers between pieces, and protected from rain and water exposure (July -November 2019). All pieces were visually inspected for the presence of selected grade-defining features that were easily identifiable by an untrained operator. Table 2-2 presents a summary of the inspection. Wane was the most frequent grade-defining
feature, appearing in 54% of the specimens, followed by saw skips (29%), and dead knots (25%). The size, position and grouping of these features have not been marked.

Table 2-1, Typical Ponderosa pine visual grade yield in “thinning from below” operations and comparison to commercial harvest.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Region</th>
<th>Grade No. 2 or better</th>
<th>Grade No. 3</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Erikson et al. 2000)</td>
<td>Grangeville, ID (Thinning)</td>
<td>47.4%</td>
<td>3.2%</td>
<td>49.4%*</td>
</tr>
<tr>
<td>(Hernandez et al. 2005)</td>
<td>Flagstaff, AZ (Thinning)</td>
<td>34.0%</td>
<td>32.2%</td>
<td>33.7%*</td>
</tr>
<tr>
<td>This study</td>
<td>Lakeview, OR (Thinning)</td>
<td>50.0%**</td>
<td>34.0%</td>
<td>16.0%***</td>
</tr>
<tr>
<td>(Smith 2021)</td>
<td>Lakeview, OR (Commercial)</td>
<td>70.0%</td>
<td>20.0%</td>
<td>10.0%*</td>
</tr>
</tbody>
</table>

*Includes economy, ** Includes 2% No. 1, ***Includes ungraded lumber.

Table 2-2, Frequency of pieces with selected grade-defining features (810 specimens)

<table>
<thead>
<tr>
<th>Defect</th>
<th>No. 1</th>
<th>No. 2</th>
<th>No. 3</th>
<th>ungraded</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wane</td>
<td>-</td>
<td>40%</td>
<td>73%</td>
<td>52%</td>
</tr>
<tr>
<td>Saw Skips</td>
<td>-</td>
<td>24%</td>
<td>37%</td>
<td>27%</td>
</tr>
<tr>
<td>Dead knot</td>
<td>-</td>
<td>26%</td>
<td>24%</td>
<td>27%</td>
</tr>
<tr>
<td>Resin pocket</td>
<td>-</td>
<td>9%</td>
<td>8%</td>
<td>8%</td>
</tr>
<tr>
<td>Bow</td>
<td>-</td>
<td>9%</td>
<td>7%</td>
<td>5%</td>
</tr>
<tr>
<td>Blue Stain</td>
<td>-</td>
<td>2%</td>
<td>6%</td>
<td>22%</td>
</tr>
<tr>
<td>Twist</td>
<td>-</td>
<td>10%</td>
<td>3%</td>
<td>4%</td>
</tr>
<tr>
<td>Crook</td>
<td>-</td>
<td>3%</td>
<td>6%</td>
<td>1%</td>
</tr>
<tr>
<td>Hole</td>
<td>-</td>
<td>0%</td>
<td>4%</td>
<td>2%</td>
</tr>
</tbody>
</table>

Total No. pieces Not Significant

388
271
132

Specific gravity and MOE of the material were determined using Metriguard E-computer Model 340 dynamic tester (Raute Metriguard 2011). The MOE calculation is based on the first mode natural frequency of the simply supported lumber (Ross 1994), where transverse vibration was induced by gently tapping the lumber at the center and data was recorded by a load cell integrated in one of the supports (Figure 2-1). The proprietary firmware also takes the distance between supports and cross section dimensions (assuming a perfect prismatic shape) as input data, but the
documentation does not explain whether the values are actually converted to static MOE values (Raute Metriguard 2011).

Moisture content was measured using a resistance moisture meter (Delmhorst, model RDM3) on every 10th lumber pulled from the unit in sequence, one layer at a time. Since the moisture content in the layers of units stored for five months in sheltered outdoor condition is not expected to vary much from one piece to another, the measured moisture content was assigned to the next nine unmeasured pieces in the same layer. Specific gravity and modulus of elasticity of the individual lumber pieces were adjusted to the reference moisture content of 12% used in NDS tables based on those measured and assigned local moisture content values. At the time of test, the overall average moisture content of all pieces was 12.9% ± 0.3%.

*Figure 2-1, MOE and specific gravity measurement using Metriguard E-computer Model 340 dynamic tester.*

Each specimen was marked with an ID, and the data related to grade-defining features along with MOE and specific gravity were recorded, so that the lumber could be traced in the prototype CLT production stage for future analysis. MOE design values for the sample groups were calculated following the ASTM D2915 standard procedure (ASTM International 2017), which covers “evaluation of allowable properties of specified populations of stress-graded structural lumber”. As per ASTM D2915 section 5.4, the sample mean MOE is considered as the design value for serviceability.
2.4 Results

The MOE distribution of all four groups (grades No. 1, 2 and 3, and the ungraded sample) are presented as boxplots in Figure 2-2. The gray clouds demonstrate the distribution of data points in each sample. The mean MOE values for grades No. 2, 3, and ungraded lumber were remarkably similar to each other (6.47 GPa, 6.54 GPa, and 6.42 GPa respectively). Grade No. 1 showed a significantly higher average MOE than the other groups (7.11 GPa), but still lower than the NDS value for No. 1 in WW (7.58 GPa, marked as the top horizontal line in Figure 2-2). Visually comparing the data clouds and the boxplots, the MOE distributions of grades No. 2, 3, and ungraded lumber were also very similar to one another (less than 2% difference in average values).

![Figure 2-2. MOE distributions and derived design values for restoration harvested Pacific PP compared to the design values published for WW species.](image)

While the mean MOE values of grades No. 1 and No. 2 fall below the respective NDS design values for WW (7.58 and 6.90 GPa respectively, marked as horizontal lines in Figure 2-2) all mean MOE values were higher than WW grade No.3. This means that, if the data are pooled together, the mean MOE value for the pooled group would be higher than WW grade No. 3 as well. The effect of grade No.1, constituting just 2%
of the population on the overall average MOE was negligible. Figure 2-3 represents the cumulative distribution of MOE for the pooled group. Based on the mean and standard deviation values, a normal distribution line was fitted to the data and a good visual match can be appreciated in the graph. The average MOE of the material for all grading groups pooled together is 6.50 GPa, which is lower than WW No. 2 but higher than WW No. 3.

Figure 2-3. Pooled MOE data values for restoration harvested Pacific PP compared to the design values published for WW species.

Table 2-3 summarizes the specific gravity and MOE design value of PP individual grade groups obtained in this study compared to WW species and previous studies. Mean specific gravity of all individual grade groups of restoration program PP were similar. Following NDS format, average specific gravity of all groups combined were calculated as 0.38 ± 0.04 at the moisture content of 12%, which was higher than 0.36 assigned to WW species in NDS supplement handbook, and higher than the values reported for PP harvested from Northern Idaho (Erikson et al. 2000). Grade No. 1 and No. 2 restoration program PP had lower MOE compared to similar grades for WW and in-grade data. However, grade No. 3 PP had higher MOE compared to grade No. 3 WW.
Table 2-3, Summary of specific gravity and average MOE of Restoration harvested Pacific PP lumber adjusted to 12 percent MC and the comparison to previous studies and commercially harvested PP.

<table>
<thead>
<tr>
<th>Location*</th>
<th>SG</th>
<th>No. 1</th>
<th>No. 2</th>
<th>No. 3</th>
<th>Other</th>
<th>Pooled Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>This Study</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SOR &amp; NCA</td>
<td>0.38</td>
<td>7.11</td>
<td>6.47</td>
<td>6.54</td>
<td>6.42a</td>
<td>6.50</td>
</tr>
<tr>
<td>STD</td>
<td>(0.04)</td>
<td>(1.01)</td>
<td>(1.56)</td>
<td>(1.61)</td>
<td>(1.54)</td>
<td>(1.54)</td>
</tr>
<tr>
<td>Erikson, 2000</td>
<td>0.36</td>
<td>6.48</td>
<td>5.90</td>
<td>5.81</td>
<td>NAb</td>
<td>6.06c</td>
</tr>
<tr>
<td>NID</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>7.05</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>STD</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>(1.35)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Green, 1987</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>7.05</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Mixed</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>(1.34)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>WW NDS</td>
<td>0.36</td>
<td>7.58</td>
<td>6.89</td>
<td>6.20</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

*Locations abbreviations: SOR- Southern Oregon; NCA- Northern California; NID- Northern Idaho (N, ID); mixed- commercially harvested lumber acquired from various US mills with unknown specific locations. a)Ungraded; b)MOE values for economy not measured; c)pooled data do not include economy.

2.5 Discussion

The fact that grades No. 1 and No. 2 restoration harvested PP lumber had lower MOE compared to the same grades for lumber harvested from commercial stands is likely a result of the presence of higher proportion of juvenile wood in the restoration program material compared to lumber generated in commercial harvesting. As mentioned in the introduction, the presence of juvenile wood reduces the mechanical properties of lumber. However, it is not easy to detect a transition line between juvenile and mature wood on a macro scale (Moore & Cown, 2017); hence the proportion of juvenile wood in individual pieces of lumber cannot be easily determined by bulk visual clues (like those used in visual grading). Currently, the presence of juvenile wood is not considered a grading criterion for structural lumber.

According to in-grade data (Green and Evans 1987) commercially harvested PP has the second lowest mechanical properties among WW species, followed only by Sugar pine (Pinus lambertiana). All grades of restoration harvested PP lumber evaluated in this study had higher mean MOE values compared to the NDS design value for WW species grade No. 3. The material was needed for production of prototype CLT specimens and could not be subjected to destructive tests to determine strength related properties. The exact correlation between MOE and other properties of restoration...
program Pacific PP could not be determined in this study and must be assumed unknown. Determination of this correlation should be a subject of a future study.

If for practical purposes it can be assumed that other properties of the lumber are directly correlated with MOE, we might also assume that the other design properties of restoration harvested PP should exceed the corresponding NDS WW No. 3 design values as well. With this assumption, the design values of WW grade No. 3 could be considered conservative approximations of design values for Southern Oregon and Northern California restoration harvested PP lumber, until exact correlations are determined.

Given the close similarities of the MOE distributions in visual grades No. 2 and No.3 with the ungraded lumber and a marginal representation of No. 1, there is a potential of pooling all grades of restoration harvested PP lumber as one class of material. This might reduce complexities in the production lines of engineered wood panels utilizing lumber from restoration thinning.

One limitation of this study is that the MOE were measured by a dynamic tester machine. The manufacturer’s description of the output provided by proprietary firmware does not specify any correction factors used to determine the static MOE from the dynamic modulus. In this study, it has been assumed that the output produces un-adjusted dynamic MOE values, which typically overestimates the static MOE. Previous studies using the same device reported a linear correlation ($R^2 \approx 0.85$) between dynamic and static MOE measurements (Wang et al. 2008; França et al. 2018). The difference between these values for PP dimension lumber obtained from small diameter trees in North Idaho was about 4% (Erikson et al. 2000). Applying similar adjustments to the dynamic MOE measured in this study does not reduce the characteristic MOE values of any group below WW grade No. 3, therefore the conclusions remain valid.

Although it is shown that the mechanical characteristics related to design values cannot be effectively differentiated by visually grading of the restoration harvested PP, by principle, grading cannot be avoided because standards for engineered wood products, such as CLT, does not permit utilization of ungraded lumber. If MSR
grading is considered as an alternative for visual grading, it should be noted that the mean MOE of the restoration program PP lumber pooled in one group does not meet the MOE qualifications of any currently established standard MSR grade. One solution that can be investigated in future studies is to define a new MSR grade specifically for restoration program PP.

Lastly, although grade-defining features such as wane, bow and twist do not influence mechanical properties of the restoration harvested material, excessive presence of such defects can be unfavorable for the use in engineered wood products. For instance, significant wanes that cannot be removed by surfacing the lumber cause gaps between lamellas of CLT which can accelerate moisture penetration when exposed to precipitation during open construction periods (Schmidt et al. 2019), and reduce acoustic and fire performance. Substantial twist in large number of laminations may be hard to overcome in pressing CLT layups. Therefore, it is suggested to apply visual limiting criteria to the restoration harvested material accordingly.

### 2.6 Conclusions

MOE distribution determined on a sample of visually graded PP lumber harvested from restoration programs in Southern Oregon and northern California was compared with design values for corresponding grades determined in previous studies and with published values for commercially harvested PP as reflected in the NDS WW species group.

Characteristic MOE values of visual grades No. 1 and 2. of PP from restoration programs considered in this study were lower than respective design values for NDS WW group. However, the mean MOE values of all groups considered individually as well as pooled together were higher than NDS WW grade No. 3. MOE distributions for all groups, except for the visual grade No. 1, were remarkably similar, showing negligible differences in the mean values.
The design values published for WW grade No. 3 in NDS supplement handbook were suggested as provisional conservative representation of the restoration program Pacific PP lumber, until proper correlations between MOE and the other design values for the material are experimentally determined.
3

Integrity of Melamine Formaldehyde Bonds in Ponderosa Pine Cross-Laminated Timber. Isolating Adhesive Compatibility Effect

Submitted to the Forest Products Journal (Winter 2022).

Co-authored by: Sina Jahedi, Lech Muszynski, Mariapaola Riggio, Sujit Bhandari.
3.1 Abstract

Integrity of melamine formaldehyde bonds in prototype cross-laminated timber (CLT) specimens was tested as part of a project on utilization of Ponderosa pine (PP) from forest restoration programs in Western US forests. Bond integrity tests, block shear and cyclic delamination, are prescribed by ANSI/APA PRG-320 to qualify new products. Of these, the cyclic delamination criterion is notoriously challenging for layups developed in research labs and pilot plants. Delamination is often blamed on poor compatibility between the adhesive and wood species, clamping pressure, and distribution of adhesive, neglecting other potential factors. One of the study objectives was to separate the effect of adhesive compatibility from other potential factors affecting bond integrity in CLT. Bonding integrity tests were conducted on prototype specimens bonded with Melamine Formaldehyde (MF) adhesive. Three types of test specimens were considered: 1) sampled from panels fabricated in a pilot-plant scale line, 2) sampled from panels fabricated in a full-scale industrial CLT plant; 3) small (102 mm x 102 mm) cross-laminated blocks. The small blocks included samples with juvenile wood and blue stain on bonded surfaces. Specimens from all samples passed the PRG-320 block shear criteria. All small blocks passed the delamination criterion, demonstrating compatibility between the adhesive and PP regardless of heavy presence of blue stain and juvenile wood. Specimens sampled from laboratory and industrial prototypes did not meet the delamination criterion. Delaminations propagated from pre-existing interlaminar gaps observed in laboratory and industrial prototype panels tracked back to thickness variation and, in pilot-plant samples, to inconsistent clamping pressure.
3.2 Introduction

Forest restoration thinning programs, are an effective way to reduce the risk of catastrophic wildfires, by selective removal of smaller or dead trees from the forest land in order to preserve superior trees (Johnston et al. 2021). These programs are expensive and every year operations in Southern Oregon and Northern California produce significant amount of low-value Ponderosa pine lumber (*Pinus ponderosa*, marked as PP from this point on), which has no remarkable market in the region (Smith 2021). This study is part of a project aimed to offset the high costs of restoration programs by exploring viability of utilizing the PP lumber in structural Cross-Laminated Timber (CLT). CLT is a massive engineered wood panel consisting of three or more orthogonally arranged plies of lumber bonded with an adhesive. Custom CLT layups are proposed for use in low-rise modular construction.

However, forest restoration programs tend to produce small-diameter logs which results in low value lumber with high proportion of juvenile wood. Compared to mature wood, juvenile wood is characterized by substantial presence of knots, high grain angle, higher microfibril angle (MFA) and thinner cell walls, which in turn translates to higher rates of shrinkage and swelling (Kretschmann 2010). The shrinkage difference between juvenile and mature wood present in the same piece of lumber is the primary cause for twist, bow, and crook after drying from green state. Lumber obtained from dead trees contains substantial amounts of blue stain, which does not significantly reduce the strength of wood (Miller 1980), but affects the visual grades. A limited study on Lodgepole pine (*Pinus contorta L.*) CLT block shear specimens bonded with polyurethane resin (PUR) demonstrated that blue stain did not affect shear resistance or wood failure (WF) percent (Li et al. 2018). The study did not address delamination. Consequently, the effect of blue stain on other common species and other adhesive systems, including melamine formaldehyde (MF), which is the focus of this study, remains unknown.

The aim of the study presented in this paper is to assess bonding integrity of PP CLT bonded with 2-component MF adhesive system. The standard criteria for bond integrity in CLT are stipulated in the North American Standard for Performance-
Rated Cross-Laminated Timber (ANSI/APA PRG 320:2019) and include resistance to cyclic delamination and the resistance to block shear tests.

3.2.1 Overview of Bond Integrity Criteria in CLT Standards

Historically, PRG-320 was first introduced in 2012 and the bond integrity tests were adapted from the American Institute of Timber Construction (AITC 2007) standard for glue laminated timber, a massive beam product with a long history, but fundamentally different from CLT in that all laminations are bonded parallel to each other. Cyclic delamination test is meant to assess bond durability through dry-wet cycles, and block shear test is meant to measure bond resistance to short term forces. These bond integrity qualification criteria were included with no major changes in all subsequent versions of PRG-320.

In Europe, the product requirements for CLT are stipulated in EN 16351 (BS EN 2015), which has been drafted and used by European industry in its project version before the publication of first North American standard. In contrast to PRG320, EN 16351 2015 allows qualification of CLT bonding integrity, based on block shear as a reference method, with cyclic delamination remaining a non-mandatory option. EN 16351 permits tests on cylindrical specimens as well as square cuts, while PRG-320 only allows square cuts. There are some major differences in the pass/fail criteria as well. In EN 16351, the maximum allowable delamination in each specimen is 10%, excluding isolated small gaps and those that are caused by knots touching on the bond line. In PRG-320, the maximum allowable delamination in each specimen is 5%, which should include all the pre-existing gaps due to adhesive failure. For block shear test, EN 16351 requires a minimum of 1.25 MPa characteristic shear strength in all specimens and a minimum 1.00 MPa shear strength in each glue line, while PRG-320 relies primarily on visual assessment of WF percent and mandates at a minimum the average of WF in all specimens to be 80%, and a minimum of 60% WF in each specimen. Shear strength is reported as a secondary criterion in AITC T107 standard to eliminate false high WF marks in specimens that exhibit significantly lower shear
strengths compared to the published values for clear wood specimens of same species.

3.2.2 Previous Studies including assessment of Adhesives and Bond integrity in CLT

Previous studies at Oregon State University were focused on qualification of small-scale laboratory-made, prototype hybrid CLT panels with Lodgepole pine cores and Douglas fir face layers bonded with PUR and phenol-resorcinol formaldehyde (PRF) adhesive systems (Larkin 2017), as well as industrial prototype hybrid CLT panels with PP cores and Douglas fir faces bonded with MF adhesive (Lawrence 2017b). In both studies, the prototype CLT layups met the PRG320 block shear resistance criteria, but failed the cyclic delamination criterion. Loose thickness tolerances of laminations was hypothesized as a potential cause for delamination (Lawrence 2017b), but the study could not effectively separate the effect of adhesive compatibility from fabrication parameters to confirm this hypothesis.

Delamination seems to be a persisting challenge in other studies as well. Table 3-1 presents a summary of a review of literature reporting outcomes of delamination tests in prototype CLT laminations presented in graph or tabular format.

Even allowing for the fact that research projects routinely test prototypes and manufacturing options of which only few may be successful, the comparison of number of reviewed projects reporting failures in the block shear tests (7 based on PRG320 and 3 based on EN 16351) to those reporting failures in the resistance to delamination tests (15 based on PRG320 and 12 based on EN 16351) indicates that the latter appears a substantially more severe criterion. Then the larger proportion of failures reported for delamination tests following PRG320 compared EN 16351 seems to reflect the difference in the qualification delamination thresholds (5% vs. 10% respectively).
Table 3-1, Summary of the reviewed projects studying bond integrity of prototype CLT laminations.

<table>
<thead>
<tr>
<th>(Author, Year)</th>
<th>Species</th>
<th>Block Shear Criterion(^{(a)})</th>
<th>Delamination Criterion(^{(a)})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Mohamadzadeh and Hindman 2015)</td>
<td>Yellow poplar</td>
<td>✓</td>
<td>×</td>
</tr>
<tr>
<td>(Hindman and Bouldin 2015)</td>
<td>Southern pine</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>(Hovanec 2015)</td>
<td>Yellow poplar</td>
<td>N/A(^{(b)})</td>
<td>✓</td>
</tr>
<tr>
<td>(Sikora et al. 2015)</td>
<td>Sitka spruce</td>
<td>✓/×</td>
<td>✓</td>
</tr>
<tr>
<td>(Liao et al. 2017)</td>
<td>Eucalyptus</td>
<td>✓</td>
<td>✓/×</td>
</tr>
<tr>
<td>(Larkin 2017)</td>
<td>Lodgepole pine, Douglas fir</td>
<td>✓</td>
<td>✓/×</td>
</tr>
<tr>
<td>(Sharifnia and Hindman 2017)</td>
<td>Southern yellow pine</td>
<td>✓</td>
<td>Not tested</td>
</tr>
<tr>
<td>(Lawrence 2017b)</td>
<td>Ponderosa pine, Douglas fir</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>(Wang et al. 2018)</td>
<td>Hem-fir</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>(Dugmore 2018)</td>
<td>Eucalyptus</td>
<td>✓</td>
<td>×</td>
</tr>
<tr>
<td>(Lu et al. 2018)</td>
<td>Eucalyptus</td>
<td>✓</td>
<td>✓/×</td>
</tr>
<tr>
<td>(Arbelaez et al. 2020)</td>
<td>Salvaged Douglas fir</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>(Mohd Yusof et al. 2019)</td>
<td>Acacia mangium</td>
<td>×</td>
<td>x</td>
</tr>
<tr>
<td>(Brunetti et al. 2020)</td>
<td>Beech spruce</td>
<td>✓</td>
<td>✓/×</td>
</tr>
<tr>
<td>(Kim 2020)</td>
<td>Japanese larch, Korean red pine</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>(Yusoh et al. 2021)</td>
<td>Tropical hardwoods</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>(Furtini et al. 2021)</td>
<td>Pinus oocarpa, Coffea arabica</td>
<td>Not tested</td>
<td>Not tested</td>
</tr>
<tr>
<td>(Ma et al. 2021b)</td>
<td>Sugar Maple, White Spruce</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>(Russel et al. 2021)</td>
<td>12 species</td>
<td>N/A</td>
<td>✓</td>
</tr>
<tr>
<td>(Jake et al. 2021)</td>
<td>10 species</td>
<td>N/A</td>
<td>✓</td>
</tr>
<tr>
<td>(Muñoz et al. 2022)</td>
<td>Gmelina arborea, Tectona grandis</td>
<td>Not tested</td>
<td>Not tested</td>
</tr>
</tbody>
</table>

% of projects reporting failures in one or more specimen groups\(^{(d)}\): 19% 38% 63% 79%

\(^{(a)}\) Based on data presented in the graphs and tables.
Of the papers that discussed potential sources contributed to observed bond integrity failures 41% quote adhesive/species compatibility, 64% quote fabrication parameters related specifically to adhesive bond formation such as uniformity of adhesive distribution, clamping pressure or press time, and only two hinted the thickness tolerances in lamstock (Sikora et al. 2015; Lawrence 2017b). Improved diagnostics should help in discriminating between cases where the bond integrity failures are actually caused by adhesive compatibility and issues related directly to the bond formation from preventable issues generated elsewhere in the fabrication process.

The objectives of this study were:

- Develop a methodology to separate the effects of adhesive compatibility from fabrication factors.
- Determine the compatibility of MF adhesive system with CLT panels made of PP harvested from restoration programs.

### 3.3 Materials and Methods

The approach involved standard PRG-320 bonding integrity tests conducted on prototype specimens bonded with 2-component MF adhesive fabricated at different scales: 1) pilot-plant scale panels, 2) full-scale panels produced in an industrial CLT plant; 3) lab-scale small (76 mm x 76 mm) cross-laminated blocks. The small blocks were intended to test the compatibility between PP wood surfaces and the MF adhesive system and were laid up with no bridging between neighboring laminations within a layer to eliminate the effect of thickness tolerance and other fabrication issues. They included samples with juvenile wood and blue stain on bonded surfaces. The samples were tested in accordance with PRG-320 for resistance to delamination and block shear.
3.3.1 Materials

The material was nominal 2 x 6 PP lumber harvested, processed, and kiln dried by Collins Lumber Co located in Lake View, OR performing contract forest restoration programs in Southern Oregon and Northern California. About 76% of the donated lumber was visually graded by the company following WWPA grading rules (WWPA 2017) and fell in the following grades: No. 1 (3%), No. 2 (48%), and No. 3 (25%). The reminder of the lumber acquired mostly from dead trees was delivered ungraded. Upon arrival to OSU about a third of the pieces were visually inspected; identified grade-defining features included wane (57% of the inspected pieces), dead knots (30%), and blue stain (7%). More detailed description of the test material is provided in a related publication (Jahedi et al. 2022a).

PRG-320 standard specifies that the thickness variation shall not exceed ±0.30 mm along the lumber length and ±0.20 mm across the width of a lamination in every 305 mm (ANSI/APA 2019). To meet these requirements, in this study an industrial scale (LeaderMac, Blaine, Washington) planer equipped with rollers with adjustable compression force to straighten the geometry defects of lumber, such as twist or bow, part of the OSU pilot plant was used to surface the lumber on four sides. When excessive twist cup or bow are not pressed flat the cutting blade removes more from the areas that stand higher, leading to uneven thicknesses. Therefore, pieces with excessive twist, cup or bow (about 0.5% of the total) were not included in the trials. Some pieces with minor twist or bow were allowed into the production. The planer was fitted with new cutting blades and fine tuned.

Thickness variation was measured on a sample of 12 straight boards planed to the target thickness of 34.29 mm. The thickness was measured on each of these pieces using a caliper (Mitutoyo, ±0.01 mm) at 36 points along the length and on both edges (864 measured points in total). The average deviation of all measured points from the target thickness was -0.01 mm (with a standard deviation of 0.09 mm and a maximum deviation of 0.53 mm).
In this study, thickness variation along the length of a lamination is defined as the difference between the maximum and minimum thicknesses measured along one edge of the lumber in the length direction. Higher than the PRG 320 thickness tolerance variation along the lamination length was detected in 7 of the 12 pieces (58%) at one or multiple points (average variation was 0.01 mm with a standard deviation of 0.09 mm, and the maximum variation of 0.83 mm).

Variation across the width is defined as the difference between the thicknesses measured on opposite edges of a lamination. Higher than the PRG 320 thickness tolerance variation across the width of the lamination was detected in 8 of the 12 pieces (67%, average variation was 0.04 mm with a standard deviation of 0.11 mm, and the maximum measured variation of 0.41 mm). These pieces were not included in the production.

Thickness tolerances in laminations planed for panels fabricated by the industrial partner have not been measured. All laminations were planed within 48 hours prior to the CLT production.

3.3.2 Specimen Fabrication

Three types of cross-laminated specimens were fabricated for the assessment of bond integrity:

- Specimens sampled from 5-ply 2.4 m x 3.0 m (8 ft x 10 ft) prototype CLT panels, with random assignment of grades in the layup, laminated at the pilot plant in the A.A Red Emmerson Advanced Wood Products Laboratory at the Oregon State University in Corvallis, OR (marked LP).

- Specimens sampled from 5-ply 3.0 m x 5.5 m (10 ft x 18 ft) prototype CLT panels, with random assignment of grades in the layup, laminated in the industrial CLT production line at DR Johnson Wood Innovations in Riddle, OR (marked IP).

- Specimens sampled from 3-ply 102 mm x 102 mm (4 in x 4 in) CLT blocks, laminated at a laboratory. The effects of thickness variations were eliminated
by laying up small sections individually so that the laminations do not bridge across blocks. The clamping plates were equipped with a rubber mat to ensure that the compression force is distributed evenly among the specimens. The same as LP and IP group, a clamping pressure of 0.68 MPa were applied to the blocks. Two samples of these blocks were fabricated:

- One with natural blue stain covering more than half of the bonded surface (marked BLB).
- The other with high content of juvenile wood, some including the pith on the bonded surfaces, but with no trace of blue stain (marked JLB).

In all samples, two-component MF adhesive systems (MF system 1263/9563; AkzoNobel, Amsterdam, Netherlands) was used. The fabrication factors were followed the manufacturer’s instructions. Spread rate was adjusted depending on the environment temperature and the desired press time, as indicated in Table 3-2. Resin and hardener components with a ratio of 100:100 were applied separately on the bond surfaces. In case of IP and LP samples, automated adhesive applicators with adjustable spread rates were used, in which the resin and hardener were applied in parallel lines and mixed together once the layup was assembled and pressed. For BLB and JLB samples, separate lines of resin and hardener were applied with syringes, on the bottom and top bond faces respectively and mixed together only when layers were put in contact to form the block layup. The resin and hardener were applied while the blocks were placed on a Mettler Teledo PB1502-S scale (±0.01 g, 0.5-1,510.0 g range). The spread rate was calculated by dividing the net weight of the resin or hardener dispensed on the blocks by the bond area. The fabrication factors for IP sample made in an industrial plant was unknown.

Following the pressing the specimens were processed in a room with average temperature of 23±3°C and 45±3% relative humidity. The LP and IP delamination and block shear specimens were cut from two corners and the center of the produced panels. BLB and JLB blocks were trimmed to final standard delamination specimen size 76 mm by 76 mm (3 in x 3 in), as much as possible excluding sections with
knots, wane, and holes to separate the effect of adhesive compatibility from that of natural wood defects.

**Table 3-2, Summary of fabrication factors.**

<table>
<thead>
<tr>
<th>Sample</th>
<th>Plies</th>
<th>Room Temp °C</th>
<th>Spread rate g/m²</th>
<th>Resin to hardener ratio</th>
<th>Close assembly time minutes</th>
<th>Press time Hour</th>
<th>Pressure MPa</th>
<th>Curing time** hour</th>
</tr>
</thead>
<tbody>
<tr>
<td>BLB</td>
<td>3</td>
<td>23±3</td>
<td>344 to 374*</td>
<td>100:100</td>
<td>30</td>
<td>24</td>
<td>0.68</td>
<td>0</td>
</tr>
<tr>
<td>JLB</td>
<td>3</td>
<td>23±3</td>
<td>344 to 374*</td>
<td>100:100</td>
<td>30</td>
<td>24</td>
<td>0.68</td>
<td>0</td>
</tr>
<tr>
<td>LP</td>
<td>5</td>
<td>23±3</td>
<td>340</td>
<td>100:100</td>
<td>40</td>
<td>3</td>
<td>0.68</td>
<td>13</td>
</tr>
</tbody>
</table>

*The prescribed spread rate for this fabrication conditions was 344 g/m². Since adhesive was applied manually, the amount exceeded for some bonds.
**Curing time refers to the conventional method of keeping the panels under reduced pressure (0.2 MPa) to stabilize the bonding.

3.3.3 Delamination Test

The cyclic delamination procedure followed PRG-320 2019 guidelines. A Mettler Teledo PB1502-S scale was used to measure the weight of specimens. All specimens were carefully inspected for pre-existing bond issues. While none were found in BLB or JLB specimens, interlaminar gaps have been found in about 17% of the LP specimens and in 20% of the IP specimens. Figure 3-1.
Figure 3-1. Examples of interlaminar gaps found in the specimens prior to tests compared to an acceptable bond.

The specimens were marked, submerged in water in a 1.7 m³ vessel, and subjected to a vacuum-pressure soak cycle consisting of a 70±20 kPa vacuum stage for 30 minutes, followed by a 520±20 kPa pressure stage for 2 hours. The saturated specimens were then placed in an oven with air circulation and constant temperature set to 70.0±0.1°C for about 13 hours until their weight was reduced to about 110% to 115% of their original weight before soaking.

After drying, the bond lines on four sides of the CLT blocks were inspected using a microscopic camera (Jiusion Magnification Endoscope, 640 by 480 pixels resolution). Images of areas with suspected delamination were taken to further analyze and to discriminate between delaminations and shallow wood failures.

PRG-320 defines delamination as a separation in bonding due to failure of the adhesive, either caused by poor bonding or low strength of the adhesive itself (Figure 3-2). Traces of wood fibers pulled off from either side of the bond surfaces indicate wood failure and do not count as delamination (Figure 3-3). The length of delamination was determined to ±1mm.
Delamination was calculated by dividing the sum of delamination lengths plus interlaminar gaps in a specimen by the total bond-line perimeter, including all bond planes, and represented as a percentage. A sample meets the PRG-320 criteria if all the specimens contain less than 5% delamination, otherwise the whole sample fails to meet the requirements.
3.3.4 Block Shear Test

Tests for the resistance to shear followed the ASTM D905 block shear test method referred by PRG-320 2019. Figure 3-4 shows the standard step specimen and test setup for block shear test. The dimensions of the bonding surfaces were measured using a ± 0.01 mm caliper. Instron universal testing machine, equipped with a 10kN capacity load cell with accuracy of ±0.4 N was used to load each bond surface to failure. The ultimate load was recorded.

![Figure 3-4. Block shear test setup.](image)

Upon completion of test, the WF percentage was assessed on both sides of the fractured bond surfaces. Since the MF adhesive is transparent under natural light, as it can be noticed in Figure 3-5 (a), ultraviolet (UV) light was used to make the adhesive visible as shown in Figure 3-5 (b). VSC8000/HS digital imaging and multi-wavelength illumination device was used to analyze the samples. After preliminary scans the best wood vs. adhesive contrast was obtained by 312nm UV light. Subsequently, this wavelength was used for the analysis of all fractured surfaces with a 4.8 Megapixel camera set to a fixed exposure time (1 s) and with the auto light adjustment function turned off.
The images were processed using a modified version of the ImageJ script (Sept 2015), which passed every pixel through a light intensity threshold and marked the ones exceeding the set threshold (Figure 3-5 -c). The ImageJ script counted the number of pixels marked as adhesive failure and calculated WF percentage accordingly. The minimum WF percentage of two sides of a bond surface was picked as the representative WF of the bond surface. To set the most accurate threshold for this study, a sample of 20 specimens was carefully investigated by comparing the traces of adhesive with those detected in the processed images.

![Figure 3-5, Images captured from bonding surface of block shear specimens and the processed image after passing through contrast threshold.](image)

### 3.4 Results

#### 3.4.1 Cyclic Delamination Test

As defined by PRG-320, delamination is the separation of laminations due to adhesive failure. Histogram in Figure 3-6 shows the distribution of delamination rates in restoration program PP CLT specimens tested for cyclic delamination. All specimens within BLB and JLB samples fabricated from blocks without possibility for bridging between adjacent laminations in a layer met the PRG-320 delamination
criteria. In specimens harvested from larger panels, 4 specimens in the LP samples and 3 in the IP samples exceeded the 5% delamination and consequently failed to meet the PRG-320 criterion. If compared to the EN 16351 delamination requirements, 3 LP specimens still fail, but all IP specimens pass the criterion.

Figure 3-6. Histogram results of cyclic delamination test of all sample samples. Number of specimens in each sample include: 20 IP, 47 LP, 27 BLB, and 14 JLB.

Microscopic observation revealed that all the specimens that had excessive amount of delamination had interlaminar gaps prior to the test, and in most cases, the propagation of interlaminar gaps was the main cause of large delamination.

3.4.2 Block Shear Test

Both IP and LP samples met the PRG-320 criterion. The average WF of all specimens within a sample and the percentage of specimens exceeding 60% WF are summarized in Table 3-3.

Table 3-3, Summary of block shear test results and comparison to the standard criteria.

<table>
<thead>
<tr>
<th>Tested Samples</th>
<th>LP</th>
<th>IP</th>
<th>Standard Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Num. of Specimens</td>
<td>36 total</td>
<td>35 total</td>
<td>3 per panel</td>
</tr>
<tr>
<td>Avg. WF of all specimens</td>
<td>90%</td>
<td>89%</td>
<td>80%</td>
</tr>
<tr>
<td>Above 60% WF specimens</td>
<td>100%</td>
<td>100%</td>
<td>95%</td>
</tr>
<tr>
<td>Characteristic Shear Strength</td>
<td>2.69 MPa</td>
<td>2.72 MPa</td>
<td>N/A</td>
</tr>
<tr>
<td>Min. Shear Strength</td>
<td>2.20 MPa</td>
<td>2.12 MPa</td>
<td>1.25 MPa</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.00 MPa</td>
</tr>
</tbody>
</table>

IP | LP | BLB | JLB
The cumulative distribution of the shear strengths determined in all bonding surfaces is shown in Figure 3-7. As the CLT plies are arranged orthogonally, the wood interface of the bond can fail in one of two modes: rolling shear or shear parallel to the grains (or a combination of these two). Rolling shear failure occurs when the fibers separate due to the shear stress exerted in the plane perpendicular to the fiber grains. The other failure mode is shear parallel to the grain which happens when the adjacent fibers slip upon another. On the graph, 66% of tested bonds that failed predominantly in rolling shear are marked with plus signs. The data were compared with shear strength parallel to grain and rolling shear strength in clear PP wood published elsewhere (Bendtsen 1976; Kretschmann 2010), shown in the graph as dotted vertical lines. Most of the test data fell in between these two values, which indicates that the block shear failure mode in cross-laminated specimens was a combination of shear parallel to the grain and rolling shear. One of the specimens with shear strength significantly lower than the benchmark rolling shear strength of clear PP wood was removed from the data pool in accordance with AITC T-107.

*Based on Wood Handbook (Kretschmann 2010).
**Estimated as \( F_v/4 \) in accordance with a previous experimental study on softwoods (Bendtsen 1976). \( F_v \) is the shear strength parallel to grain.

Figure 3-7. Cumulative distribution of shear strength of specimens.
The characteristic shear strength of the samples was calculated by finding the 5th percentile tolerance limit of the data, 2.69 MPa for the LP sample and 2.72 MPa for the IP sample. Both values exceed the 1.25 MPa characteristic shear strength and all bonding surfaces had above 1.0 MPa shear strength, meaning that all samples have met the EN 16351 criteria, Table 3-3.

Table 3-4, Test results compared to pass and fail criteria of American and European standards.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Delamination Requirements</th>
<th>Block Shear Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PRG-320</td>
<td>EN 16351</td>
</tr>
<tr>
<td></td>
<td>All spec. &lt;5%</td>
<td>All spec.&lt;10%</td>
</tr>
<tr>
<td>BLP</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>JLP</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>LP</td>
<td>× (4 out of 47)*</td>
<td>× (3 out of 47)*</td>
</tr>
<tr>
<td>IP</td>
<td>× (3 out of 20)*</td>
<td>✓</td>
</tr>
</tbody>
</table>

|        | PRG-320                   | EN 16351                  |
|        | >WF_{Avg.}                | >1.25 MPa_{char Str.}     |
|        |                             | >1.0 MPa_{all bonds}      |

*Number of specimens failed compared to the total number of specimens tested in that sample.

In Table 3-4, the results of cyclic delamination and block shear tests for all samples are compared to the bond integrity requirements of PRG-320 and EN 16351 standards.

3.5 Discussion

All tested cross-laminated samples passed both PRG-320 and EN 16351 block shear criteria. No significant difference between IP and LP samples was found (based on one-way ANOVA with confidence level of 0.95). However, 4 specimens in the LP sample and 3 in the IP sample exceeded the 5% delamination and consequently failed to meet the PRG-320 criterion. One possible cause for these gaps might be the higher than allowed per PRG 320 thickness variations in LP laminations planed with the industrial-scale planer. It is possible, but not certain at this point, that presence of the moderate twist and bow in the lumber that was allowed in the test material contributed to increase the thickness variations even further.
It was also observed that all of the LP specimens with delamination rates exceeding 5% were obtained from the center of the panels, while none of the specimens obtained from corners had high delamination percentage. Similar failures in laminates examined in parallel projects drew the attention to the possibility of uneven clamping pressure distribution due to the insufficient rigidity of the retractable tray used in the pilot plant press, which might have deflected under high pressures. If this hypothesis is confirmed, the effect might have contributed as well. Combined, both effects might explain the presence of interlaminar gaps in LP samples, but not in the IP specimens sampled from panels produced on the industrial line.

Cyclic delamination test on small CLT blocks (BLB and JLB) demonstrated good compatibility between MF adhesive and PP lumber from restoration forest programs despite substantial presence of blue stain or juvenile wood. That way, the effect of adhesive compatibility was separated from issues related to other fabrication factors substantially enhancing the diagnostics. However, we were not able to pinpoint the exact fabrication issue that caused poor bonding.

Given that delamination seems to be a challenging criterion for other projects as well, a future study is needed to isolate thickness tolerances from other fabrication parameters.

### 3.6 Conclusion

In this study a method enhancing diagnostics of adhesive bond integrity failures in CLT was proposed in which the effects of adhesive compatibility were separated from other fabrication issues.

The method was used to diagnose potential causes of delamination failures in prototype CLT panels in which Ponderosa pine laminations from logs harvested in forest restoration programs were bonded with MF adhesive.

It is concluded that MF adhesive systems is compatible with restoration program PP, regardless of the presence and amount of blue stain and juvenile wood. However, the
material sampled from the large-scale, prototype panels failed to meet the delamination criterion.

The enhanced method allowed exclusion of adhesive incompatibility as a potential cause of delamination despite the presence of pre-existing interlaminar gaps detected in those specimens obtained from large-scale panels. While the specific cause for the existence of the inter-laminar gaps could not be specifically identified, partial evidence collected on the pilot-scale fabricated panels pointed at either wide thickness tolerances in laminations, or inconsistent clamping pressure, or a combination of both. There was not enough data to speculate on the cause of interlaminar gaps in industrially-made CLT panels.
4

Mechanical Characteristics of Custom CLT Layups Laminated by Ponderosa Pine Harvested from Restoration Programs


Co-authored by: Sina Jahedi, Lech Muszynski, Mariapaola Riggio, Sujit Bhandari.
4.1 Abstract

National forest restoration programs aimed at effective mitigation of catastrophic wildfires and pest outbreaks in Western region of the United States yield a substantial amount of small diameter Ponderosa pine logs. Lumber produced from these logs is considered low-value due to lower mechanical properties compared to commercially harvested lumber. US Forest Service is seeking a value-added market for this material to offset the high costs of the forest restoration operations. Cross laminated timber (CLT) is considered one of the potential markets for the material. This study was a part of a larger project aimed at determination of feasibility of utilizing CLT fabricated from restoration harvested Ponderosa pine in a class of low-rise modular mass-timber construction. A CLT layup was designed based on the design requirements of a modular construction system determined in a parallel study. The mechanical characteristics of that layup were empirically verified through mechanical tests on prototype panels, three fabricated at a pilot-plant line at Oregon State University and two at an industrial manufacturing line. In all prototypes, grades No. 1, 2, 3 and ungraded laminations were assigned to all layers randomly. Standard ASTM D198 methods for long- and short-span flatwise bending tests were conducted to derive effective moment capacity, effective stiffness, and shear capacity of the layups. Optical measurement based on digital image correlation was used to derive effective shear rigidity of the specimens. There was no significant difference between the results obtained from the prototypes fabricated in the pilot-plant compared to those fabricated in an industrial setting. The outcomes of mechanical tests indicate that the prototype CLT panels exceeded the structural requirements. The effective moment capacity, stiffness, and shear rigidity were higher than the values estimated by the shear analogy method. Shear capacity was lower than predicted. It is concluded that the restoration program PP CLT layups can be custom designed to meet mechanical requirements for structural elements in certain class of modular buildings.
4.2 Introduction

Forest restoration thinning programs are essential measures to mitigate catastrophic wildfires and pest out-breaks in the Western forest lands. In these operations, smaller and dead trees are selectively harvested to preserve larger and superior trees in the forest land (Graham et al. 1999). Each year, restoration programs in Pacific Northwest yield a substantial amount of Ponderosa pine, *Pinus ponderosa*, (PP) lumber generated mostly from small-diameter logs, containing significant amounts of juvenile wood, wane, and prone to twist. The majority of that lumber is considered low-value (Rainville et al. 2008) and it is not typically used for structural purposes (Smith 2021). United States Department of Agriculture (USDA) Forest Service is seeking a value-added market for PP lumber generated in restoration programs to offset the high costs of these operations.

Cross-laminated timber (CLT) is considered one of the potential markets for such material (Lawrence 2017a). CLT is a structural engineered wood panel comprised of at least three orthogonal laminations of graded lumber bonded with a structural adhesive. The idea of utilizing low-grade lumber in engineered wood products is not a new concept. Research on small diameter yellow-poplar, *Liriodendron tulipifera*, (Mohamadzadeh and Hindman 2015), fast-grown eucalyptus, *Eucalyptus grandis*, (Liao et al. 2017), Monterey pine, *Pinus radiata*, (Sigrist and Lehmann 2014), and sugar maple, *Acer saccharum*, (Ma et al. 2021a) demonstrated that low-grade lumber can provide satisfactory structural properties if utilized in CLT. Another study showed that PP lumber obtained from small-diameter trees can be successfully utilized in fabrication of structural glue-laminated timber (Hernandez et al. 2005).

The feasibility of hybrid CLT panels consisting of structural grade lumber for outer layers and low-grade Lodgepole pine, *Pinus contorta*, (Larkin 2017) and mixed restoration harvested species including PP (Lawrence 2017b) in the inner layers was studied at Oregon State University. These studies demonstrated that the custom hybrid CLT panels had strength and stiffness comparable with E3 CLT grade as defined in PRG-320.
The requirements for fabrication, performance, and quality assurance of CLT panels produced and used in North America are specified in ANSI/APA PRG-320 standard for performance-rated CLT (ANSI/APA 2019). Based on the standard, visually graded No. 2 or better lumber can be used in layers aligned with the major strength direction of the panel and No. 3 or better lumber can only be used in layers aligned with the minor strength direction of standard CLT panels. However, the standard permits fabrication of custom layups, as long as all laminations are visually or machine graded, and the CLT layup meets stipulated performance criteria.

Mechanical characteristics of CLT panels can be predicted based on the properties of laminations arranged in the layup. For this purpose, PRG-320 refers specifically to the shear analogy method (Kreuzinger 1999). The calculations are typically conducted based on the reference design values published in the National Design Specification (NDS) supplement handbook (American Wood Council 2018) for commercially harvested lumber of species and species groups. In this document, the design characteristics for commercially harvested PP are provided as part of the “Western Woods” (WW) species group. However, previous studies indicate that the lumber harvested from restoration programs has lower mechanical properties compared to commercially harvested material due to presence of substantially larger proportion of juvenile wood (Erikson et al. 2000; Vaughan et al. 2021; Jahedi et al. 2022a). Consequently, visually graded lumber harvested from restoration programs often does not meet the NDS design characteristics of similar grades (Erikson et al. 2000; Hernandez et al. 2005; Jahedi et al. 2022a). Instead, it has been proposed that the highest visual grade in NDS that actually matches the mechanical characteristics of the lumber generated in restoration thinnings could be used for designing custom CLT layups.

The next difficulty is defining a structural application with a potential for utilization of such CLT panels in substantial volumes. Due to large size and weight, mass timber panels cannot be custom fabricated on the construction site. Panels have to be prefabricated for specific projects and there is no commodity market for unfinished mass timber panels. Current mass timber panel construction in North America is still
focused on high-profile, often tall and first of their kind structures calling for high-grade CLT panels. It seems much more likely that low-rise modular structures may present such outlet for panels of lower grades, by providing the chance to produce a large number of similar units for a particular end-use, such as temporary classrooms, affordable housing units or medium to long-term emergency housing.

Creating a prototype design of such modular structures specifically aimed at using CLT panels fabricated from restoration harvested PP has been the focus of a parallel study (Bhandari 2022). The study also assessed the minimum mechanical characteristic requirements for the CLT panels to be used in such structure.

The goal of this study was to assess the mechanical characteristics of CLT panels made from PP generated in forest restoration thinnings for specific class of applications in low-rise modular buildings. The specific objectives were to:

- Determine a custom layup for PP CLT that meets the design requirements of the modular structure proposed by Bhandari et al. (2022).
- Experimentally quantify the relevant mechanical characteristics of the prototype panels fabricated based on that custom layup.
- Determine the impact of fabrication scale on the mechanical characteristics of the prototype panels.

4.3 Materials and Methods

The general approach of the study was to 1) design a CLT layup using the shear analogy method based on the requirements of the target structural design; and 2) experimentally verify the selected mechanical characteristics of the resulting CLT layups relevant for that type of structure. The focus was on standard long- and short-span flatwise bending tests in the major strength direction to derive effective moment capacity $F_{b,S_{eff,f,o}}$, effective stiffness $E_{I_{eff,f,o}}$, and shear capacity $v_{s,o}$. Strain fields in the shear span of the specimens were measured using an optical system to derive effective shear rigidity $G_{A_{eff,f,o}}$. The edgewise and minor strength directions were not critical for the structural panel elements in the proposed design (Bhandari 2022).
The prototype CLT panels were fabricated following the theoretical layup design in two scales: in a pilot-line scale at Oregon State University (OSU) and in a full-scale industrial setting at a DR Johnson Wood Innovations CLT manufacturing plant.

4.3.1 Design of Custom PP CLT Layups

The shear analogy method (Kreuzinger 1999) as formulated in PRG-320, Appendix X3, was adopted in a computer application, named Layup-App (Jahedi et al. 2020), whose objective was to find a CLT layup with minimum gross thickness that meets the structural requirements dictated by the modular building designed for this project. These requirements were the minimum ASD reference design values to satisfy the bending and shear criteria per NDS, short term and long-term deflection criteria per IBC 2018, and vibration criteria per CLT Handbook for a 3.6 m (12ft) span simply supported floor. A total dead load of 2.4 kN/m² (50 psf) including self-weight, and a live load of 1.9 kN/m² (40 psf) were considered in the analysis. The minimum building requirements are labeled as “Target Values” in Table 4-3.

As discussed in the Introduction, NDS design characteristics for visually graded PP lumber could not be used directly for the material generated in restoration thinnings. Previous study analyzed MOE values of PP lumber from restoration thinnings performed in Southern Oregon and Northern California visually graded as No. 1, No. 2, No. 3, as well as ungraded lumber sawn mostly from dead trees (Jahedi et al. 2022a). Lumber graded as No. 1 (a marginal fraction of the analyzed lumber) and No. 2 did not meet the NDS MOE characteristics for respective visual grades of WW specie group which include PP. However, average MOE values of all visual grades and of the ungraded material were higher than NDS WW grade No. 3. No statistically significant difference was found in MOE values determined between visual grades No. 2, No. 3 and the ungraded lumber. Hence, it has been proposed that the design characteristics of PP lumber from restoration thinnings could be conservatively assumed as corresponding to those of NDS WW No. 3. It was further proposed, that pooling the restoration PP lumber regardless of the visually assigned grade for the purpose of designing project specific custom CLT layups may allow to maximize
material utilization and reduce production costs (Jahedi et al. 2022a). That hypothesis was tested in this study. Namely, that any PP lumber meeting the minimum visual grade requirements of WW No. 3 can be used in the CLT layup. Consequently, the design values of WW grade No. 3 as presented in NDS, Table 4A, were used to represent the mechanical characteristics of restoration program PP laminations assigned for longitudinal and transverse directions.

Figure 4-1, Flowchart of the Layup-App developed to find a CLT layup meeting the building requirements.

A general flowchart of the Lay-up-App is shown in Figure 4-1. The approach was to start with a 3-ply CLT layup with the thinnest laminations permitted by PRG-320 (16 mm) and use the shear analogy method to calculate the design characteristics of the layup. If the layup design characteristics were lower than the design requirements, i.e., allowable $F_p S_{eff, f}$, $E I_{eff, f}$, $v_s$ and $G A_{eff, f}$, the thickness of all individual laminations was increased by 3 mm to perform another iteration. In the case that the lamination thicknesses exceeded 51mm, that is the maximum permitted by PRG-320, another pair of laminations were added to the layup and the thickness of all
laminations were set to 16 mm again. Although the Layup-App allows using various thicknesses for each layer, this application was limited to symmetric layups with the same thickness for all layers in order to reduce manufacturing complications.

The solution best matching the structural design requirement was a 5-ply CLT layup with a gross thickness of 168 mm. This finding informed the next stage of the project for fabrication of CLT prototypes. The design values of the layup are presented in Table 4-3, labeled as "Shear Analogy Est.", in the results section and were compared to the experimentally derived design values.

4.3.2 Fabrication of Prototype PP CLT

The custom PP CLT prototypes were fabricated using 2 x 6 nominal dimension PP lumber obtained from Southern Oregon and Northern California restoration operations performed by Collins Co. (Lakeview, OR). Total amount of 63.7 m$^3$ (27,000 Bdft) lumber was kiln dried, and visually graded by the company: 50% of material as No. 2 or better and 35% as No. 3. The remaining 15% of the material sawn mostly from dead trees was delivered ungraded. The material was stored in a roofed outdoor shed in tight units with the original wrapping. The average moisture content of the boards determined at the time of the panel fabrication was 10.8% ± 1.1.

One of the goals of this study was to investigate the impact of fabrication scale on the performance of the prototypes, therefore, samples were made in a laboratory and in an industrial setting and were subjected to the same tested. 7.4 m$^3$ (3150 Bdft) of the lumber were used to fabricate laboratory prototypes (LP) panels at the A.A. ‘Red’ Emmerson Advanced Wood Products Laboratory, Oregon State University. Also, a 8.3 m$^3$ (3500 Bdft) portion of the lumber was sent to DR Johnson Wood Innovation, a CLT manufacturing plant located at Riddle, OR, to fabricate industrial prototypes (IP) panels.

For LP prototypes, the material was planed on four sides using a medium scale industrial planner (LeaderMac, Blaine, Washington) available at OSU pilot plant to achieve uniform thicknesses and to refresh the surfaces for a good bonding. For optimal performance, the machine was equipped with brand new cutting blades.
Following PRG-320, the thickness variations across the width of a lumber shall not exceed ±0.20 mm in every 305 mm width and ±0.30 mm along the length. Right after planning, the thickness of 12 lumber specimens were measured (using a Mitutoyo caliper with a ±0.01) at 36 points along the length on each edge of the lumber, 72 measurement points on each specimen. The average of measured variations across the width of lumber was 0.04 mm (with a standard deviation of 0.11 mm and a maximum of 0.41 mm), and the average variation along the length was 0.01 mm (with a standard deviation of 0.09 mm and a maximum of 0.83 mm). In total, 8 out of 12 specimens failed to meet the PRG-320 thickness tolerances criteria in one or multiple points. These pieces were excluded from the production. No data on lamination thickness variation is available for the IP sample made by the industrial partner. All laminations were planed within 48 hours of production.

For both LP and IP samples, lumber pieces from all graded groups and from the ungraded group was assigned to all layers randomly. The 5-ply prototype layups were bonded using two-component melamine formaldehyde adhesive system (AkzoNobel 1263_9563, Amsterdam, Netherlands). Fabrication factors were set as per adhesive manufacturer's guidelines. For the LP sample, adhesive was spread by a semi-industrial Hexion applicator with a spread rate set to 340 g/m² and a resin to hardener ratio of 100:100. The layup were pressed for 3 hours under a 0.68 MPa pressure using a semi-industrial Minda press. The IP sample were produced using fabrication factors similar to a typical production in the plant, however the exact values were not available.

The specimens required to conduct the targeted mechanical tests were obtained from three 2.43 m by 3.05 m LP CLT panels and two 3.05 m by 5.49 m IP CLT panels with major direction oriented along the length of the panels, (Table 4-1). While PRG-320 specifies a span to depth ratio of 30 for long span bending tests, achievable ratio for LP sample was restricted by the size of the CLT press in the pilot-plant which allowed fabrication of panels up to 3.05m length.

The goal of three-point bending tests was to measure the rolling shear strength of the panels. That is why PRG-320 and ASTM D198 specify a relatively small span to
depth ratio (between 5 to 6) to ensure rolling shear failure, rather than failure in bending. The short-span LP specimens were cut with a span to depth ratio equal to 6 and it was observed that half of them failed in bending, and their ultimate rolling shear strength remained unknown. Therefore, the span to depth ratio of IP specimens were reduced to 5.5 to ensure rolling shear failure.

Visual inspection revealed presence of pre-existing interlaminar gaps in 15 (88%) of LP and 23 (76%) of IP bending specimens. On average interlaminar gaps covered 0.9% of the bond line perimeter of LP and 1.8% of the IP bending specimens. The produced prototype panels were also used to extract bond integrity test samples, which are reported in a separate publication (Jahedi et al. 2022b). The outcomes showed that, these interlaminar gaps were the main cause for poor resistance to delamination. The study isolated the impact adhesive/species compatibilities and demonstrated that the interlaminar gaps are caused due to some fabrication issues, potentially high thickness variations within laminations, uneven clamping pressure, or a combination of both.

Table 4-1 Summary of the tests performed, number of specimens and dimensions.

<table>
<thead>
<tr>
<th>Type of Tests</th>
<th>Sample Group</th>
<th>No. of Spec.</th>
<th>PRG-320 Span/Depth</th>
<th>This Study Span/Depth(^{(a)})</th>
<th>Length, Width and Depth mm x mm x mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Third-Point Bending</td>
<td>LP</td>
<td>11</td>
<td>30</td>
<td>17.2</td>
<td>3,040 x 300 x 168</td>
</tr>
<tr>
<td></td>
<td>IP</td>
<td>14</td>
<td>30</td>
<td>30.6</td>
<td>5,483 x 300 x 174</td>
</tr>
<tr>
<td>Three-Point Bending</td>
<td>LP</td>
<td>6</td>
<td>5 to 6</td>
<td>6.0</td>
<td>1,158 x 300 x 168</td>
</tr>
<tr>
<td></td>
<td>IP</td>
<td>16</td>
<td>5 to 6</td>
<td>5.5</td>
<td>1,114 x 300 x 174</td>
</tr>
</tbody>
</table>

\(^{(a)}\) Half of bearing support (76mm from each side) was deducted from the actual length when span was calculated.

4.3.3 Mechanical Tests

All tests performed in this study are summarized in Table 4-1. The third-point bending test method specified in ASTM D198 standard, sections 4 through 12, was followed to determine flatwise effective moment capacity \( F_{b}S_{eff,f,0} \) and effective
stiffness $EI_{eff,f,0}$. Also, three-point bending test was conducted on short beams following the same standard to derive flatwise shear capacity $v_{s,0}$. In both types of tests, a LVDT sensor was installed on a yoke suspending from the reaction points to measure total deflection of the neutral axis at the center of the beams. In addition, another LVDT sensor was used in the third-point bending test to measure the deflection of the neutral axis in the shear-free span between the loading points. An optical measurement system based on the digital image correlation (DIC) principle, by Correlated Solutions (Schreier et al. 2009), was used to measure the shear strains $\varepsilon_{xy}$ in the shear span to determine flatwise effective shear rigidity $GA_{eff,f,0}$, Figure 4-2.

Figure 4-2, Third-point (top) and 3-point (bottom) bending test setups. The field of view of the optical system is marked in red. LVDT sensors that were extended through the length were installed behind the beams and not shown in the images.
The mechanical properties were derived using equations presented in ASTM D198, Table X2.1. A load duration adjustment factor \(C_D = 1.6\) was applied to the maximum shear and bending loads to compensate for actual duration of the tests (10 minutes) compared to ten years live load duration used to derive shear analogy values. Additionally, 5\textsuperscript{th} percentile tolerance limit of the data divided by a safety factor \(C_{ASD} = 2.1\) was considered to derive strength related design values, i.e. \(F_b S_{eff,f,0}\) and \(v_{s,0}\), (ANSI/APA 2019). While the number of specimens fabricated and tested in this study meets the standard requirements, the sample size was too small to determine the 5\textsuperscript{th} percentile datapoint directly from the pooled data. However, for normally distributed data, it is possible to calculate the 5\textsuperscript{th} percentile tolerance limit from Equation 4-1, where \(\mu\) is mean and \(\sigma\) is the standard deviation of the data. The normality of the data was confirmed using the Shapiro-Wilk method, suitable for sample size smaller than 20 (Mishra et al. 2019).

\[x_{5\text{th percentile}} = \mu - 1.64 \sigma\]  \hspace{1cm} \textit{Equation 4-1}

For deflection related design values, i.e. \(EI_{eff,f,0}\) and \(GA_{eff,f,0}\), the averages of respective measured values for all specimens were used. In PRG-320, the ASD reference design values are presented per a unit of width, i.e. per 1 ft of the width of the structural element. For consistent use of the metric system, these design values were converted from 1 ft of width to 1 m of width. The application of the adjustments is summarized in the set of equations 2-5:

Effective moment capacity: \[F_b S = \frac{F_b S_{S\%}}{C_D C_{ASD}}\]  \hspace{1cm} \textit{Equation 4-2}

Effective stiffness: \[EI = EI_{av}\]  \hspace{1cm} \textit{Equation 4-3}

Effective shear capacity: \[v_s = \frac{v_{S\%}}{C_D C_{ASD}}\]  \hspace{1cm} \textit{Equation 4-4}

Effective moment capacity: \[GA = GA_{av}\]  \hspace{1cm} \textit{Equation 4-5}

Average shear strain of the specimens through the entire beam depth was acquired from the shear span of the beam as shown in Figure 4-2. The area of interest in the camera view is located at a 10 mm from the load point, to avoid impact of stress concentration around the load point on the results. The average of shear strain
\((\varepsilon_{xy\ av})\) in all measurement points within the area of interest spaced 7 pixels apart were used in Equation 4-6 to derive effective shear moduli, \(G_{eff,f,0}\), of the beams where, \(\tau_{av}\) is the average shear stress on the cross section of the beam, \(P\) is the total load force exerted, \(b\) is the width, and \(h\) is the depth of the beam.

\[
G_{eff,f,0} = \frac{\tau_{av}}{\varepsilon_{xy\ av}} \tag{Equation 4-6}
\]

\[
\tau_{av} = \frac{P}{2b h} \tag{Equation 4-7}
\]

### 4.4 Results

The modulus of elasticity (MOE), true elastic modulus (\(E_{true}\)), shear modulus, (G) and modulus of rupture (MOR) of prototype CLT samples determined in the third-point bending and in the three-point bending on short beams are presented in Table 4-2.

**Table 4-2 Summary of effective mechanical properties of PP CLT prototype specimens.**

<table>
<thead>
<tr>
<th>Bending Test</th>
<th>Sample</th>
<th>MOE (GPa)</th>
<th>(E_{true}) (GPa)</th>
<th>(G^{(a)}) (GPa)</th>
<th>MOR (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Avg</td>
<td>Std</td>
<td>Avg</td>
<td>Std</td>
<td>Avg</td>
</tr>
<tr>
<td>Third-Point</td>
<td>LP</td>
<td>6.0</td>
<td>0.5</td>
<td>6.3</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>IP</td>
<td>4.4</td>
<td>0.5</td>
<td>5.2</td>
<td>0.5</td>
</tr>
<tr>
<td>Three-Point</td>
<td>LP</td>
<td>6.0</td>
<td>0.6</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>IP</td>
<td>2.5</td>
<td>0.2</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

*No safety factors were applied to the values. \(^{(a)}\) Shear modulus values are calculated using DIC optical measurements.*

In the table, the average MOR values for short beams tested in three-point bending includes nominal MOR values of the specimens that failed in rolling shear as well as those that failed in flexure. However, the short beam specimens that failed in flexure were not included to derive the shear capacity design values.

The cumulative distributions of experimentally derived values are compared to the ASD reference design values estimated through the shear analogy method in Figures
3-6. The triangles and circles represent data points belonging to individual specimens for LP and IP groups respectively. Values are presented with safety and adjustment factors applied. Design values of basic grade E3 CLT with a similar layup are included in the graphs for comparison.

**Figure 4-3**, Cumulative distribution of experimentally derived effective flatwise moment capacity values compared to shear analogy estimates and basic E3 CLT grade with the same layup.

**Figure 4-4**, Cumulative distribution of experimentally derived effective flatwise stiffness values compared to shear analogy estimates and basic E3 CLT grade with the same layup.
Figure 4-5, Cumulative distribution of experimentally derived effective flatwise shear capacity values compared to shear analogy estimates and basic E3 CLT grade with the same layup.

Figure 4-6, Cumulative distribution of effective flatwise shear capacity values derived from short- and long-span (third-point and three-point) bending tests compared to shear analogy estimates and basic E3 CLT grade with the same layup.

Shapiro-Wilk test showed that all groups, except shear rigidity for long span IP, met the normality criterion, therefore cumulative normal distribution lines were fitted to the data in the Figures 3-6. The intersection of the 5th percentile horizontal lines for moment and shear capacity and the 50th percentile for stiffness and shear rigidity with the fitted normal distribution lines indicate the reference design values for each group.
The experimental design values at the 5\textsuperscript{th} percentile tolerance limit for strength related properties were determined numerically using Equation 4-1 and adjustment factors were applied. The design values for the deflection related properties were calculated as the mean values of the experimental data, following PRG-320. The results are summarized in Table 4-3.

<table>
<thead>
<tr>
<th>Numerically derived</th>
<th>Moment Capacity</th>
<th>Stiffness</th>
<th>Shear Rigidity</th>
<th>Shear Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$F_{bS_{eff,0}}$</td>
<td>$E_{I_{eff,0}}$</td>
<td>$G_{A_{eff,0}}$</td>
<td>$v_{s,0}$</td>
</tr>
<tr>
<td>Target values((a))</td>
<td>7.4</td>
<td>1262</td>
<td>4.3</td>
<td>8.0</td>
</tr>
<tr>
<td>E3 basic grade</td>
<td>25.4</td>
<td>2469</td>
<td>9.5</td>
<td>26.5</td>
</tr>
<tr>
<td>Shear analogy est.</td>
<td>8.2</td>
<td>1941</td>
<td>9.5</td>
<td>34.1</td>
</tr>
<tr>
<td>Experimentally derived</td>
<td>long-span</td>
<td>short-span</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LP</td>
<td>20.4</td>
<td>2465</td>
<td>78.1</td>
<td>74.1</td>
</tr>
<tr>
<td>IP</td>
<td>19.7</td>
<td>2254</td>
<td>72.3</td>
<td>67.6</td>
</tr>
</tbody>
</table>

All design values are ASD reference. Safety and adjustment factors per PRG-320 were applied to the values above. \((a)\)The minimum design values requirements for the building designed for this project.

One-way ANOVA test with a confidence level of 95\% were performed on the test data of similar bending samples, and the results showed that the outcomes of IP and LP are not significantly different in any group. It can be discussed that the fabrication scale/environment does not have a significant impact on the mechanical properties of PP CLT.

### 4.5 Discussion

All the experimentally derived mechanical characteristics met the structural requirements. The effective moment capacity, effective stiffness, and effective shear rigidity design values for IP and LP exceeded the shear analogy estimates calculated.
using NDS reference design values for WW No. 3 lumber. However, the experimental shear capacity design values were about 40% lower than the shear analogy estimates. The findings partially validate the assumption that the PP lumber from forest restoration thinnings pooled in one group regardless of the visual grade assignment can be considered as a standalone class of material, and that NDS WW grade No. 3 conservatively represents the mechanical properties.

One potential reason for the low shear capacity may be the presence of interlaminar gaps detected in 80% of the specimens. These gaps led to delamination failures in standard bond integrity tests observed in a parallel study conducted within this project (Jahedi et al. 2022b). The working hypothesis is that these interlaminar gaps may have resulted from a combination of high thickness variations along the laminations and uneven clamping pressure.

A large difference (by a factor of x7.8 for LP and x7.1 for IP) exists between the shear rigidity design values derived empirically and the shear analogy estimates. The reason for this may lay in the peculiar assumption used in the formulation of the shear analogy method offered in PRG-320 which indicates a proportional relationship between the shear modulus $G_0$ and the elastic modulus $E_0$ in the longitudinal direction, to be $G_0 = E_0/16$ for all species. The rationale for this assumption dates back to 1970s from previous experiments on clear specimens that suggested that the proportion between the shear modulus and the true elastic modulus falls between 1/12 to 1/20 (Samson and Sotomayor-Castellanos 1991). However, that ratio for clear PP specimens reported in FPL 2010 Wood Handbook is 1/7, (Kretschmann 2010), which is significantly larger than the 1/16 ratio assumed in PRG-320 for all species. Furthermore, this assumption should not be applied to strength-graded lumber, where the characteristic elastic modulus is highly related to the grade-defining characteristics, such as number, size and position of knots and the slope of grain. In fact, empirical studies suggest that the shear modulus in dimension lumber is independent of lumber grade (Khokhar, et al., 2008).

While the experimentally derived characteristics are closer to the actual characteristics of the layup, it shall be noted that PRG-320 considers the shear
analogy method as a primary practice to calculate the reference design values of custom layups. The mechanical tests are meant for validation of the characteristics derived from the shear analogy method. Therefore, in this study, the shear analogy estimates for effective moment capacity, stiffness, and shear rigidity, presented in Table 4-3, shall be used as the primary design characteristics for engineering purposes. However, since the experimentally derived shear capacity was lower than predicted, the experimental value (19.3 kN/m) shall be selected as the ASD reference design value.

While the aim of this project was to demonstrate the potential of custom PP CLT layup for a specific type of modular construction, CLT manufacturers shall officially certify the layups produced in their facility.

### 4.6 Conclusion

A custom CLT layup meeting the requirements of a low-rise modular building design was determined using an iterative computer algorithm that was based on the shear analogy method. The design values were derived assuming PP lumber harvested from restoration programs in Southern Oregon and Northern California will be used in all layers regardless of assigned visual grades.

Prototypes of the resulting CLT layup with random grade assignment in all layers were fabricated at a pilot-plant at the Oregon state University and on an industrial line operated by a commercial CLT manufacturer. All empirical design characteristics met the requirements of the target modular building designed considered in this project. Furthermore, both samples shown higher effective moment capacity, stiffness, and shear rigidity than the design values estimated with the shear analogy method, but the shear capacity was lower than the estimated value.

Substantial discrepancy between experimentally derived shear capacity and shear analogy method estimates, can likely be attributed to the interlaminar gaps detected in 80% of specimens. For specimens fabricated at the pilot-scale line the gaps may have resulted from a combination of poor thickness tolerance of the laminations and
uneven clamping pressure distribution. However, there is no sufficient evidence to explain the existence of interlaminar gaps in panels fabricated in the industrial CLT line.

The fact that the shear analogy method underestimated shear rigidity of CLT layups was likely related to the assumed universal proportional relationship between shear modulus and elastic modulus for all softwood species and lumber grades based on correlations found in small clear specimens.

It is concluded that the restoration program PP CLT layups can be custom designed to meet mechanical requirements for structural elements in certain class of modular buildings.
5

Summary of Outcomes and Discussions
The outcomes of this study are summarized in this section and the results presented in the previous sections are interpreted in the context of the overall project goals. These were to assess the feasibility of using restoration program PP CLT for a specific type of low-rise modular building. The presented study was focused on a material level assessment which included: determining characteristics of restoration program PP lumber, evaluating bond integrity of layups bonded with MF adhesive, designing an optimized CLT layup meeting the building requirements, and assessing mechanical performance of resulting PP CLT layup.

5.1 Characteristics of Restoration Program PP Lumber

PP is one of the species in NDS WW group which has lower mechanical properties compared to other softwood species commonly used for fabrication of CLT in North America, such as Larch-Douglas fir, Southern yellow pine, and Spruce-pine-fir species groups. Furthermore, PP has the second lowest mechanical properties among WW species, followed only by Sugar pine. Restoration program lumber yield a subgroup of PP, obtained from small-diameter trees, characterized by even overall lower quality. The material acquired for this project majorly contained wane and dead knots, therefore, more than half of them was visually graded as No. 3 or below. Although a portion of the lumber was visually graded as No. 1 and No. 2, the characteristic MOE values of those groups, determined non-destructively, were lower than corresponding grades of commercially harvested material. Most likely, this was due to presence of high contents of juvenile wood in the restoration program lumber. Juvenile wood has lower strength and stiffness compared to mature wood. However, it is not easy to detect a transition line between juvenile and mature wood on a macro scale inspection. The ratio of juvenile to mature wood was not measured in this study, but the presence of juvenile wood was traceable from the presence of the pith in the lumber.

All groups of restoration harvested PP lumber used in this study had higher characteristic MOE compared to WW species grade No. 3. As discussed in Section 2.5, for practical purposes, it can be assumed that other properties of the lumber are
correlated with MOE. Therefore, it was speculated that the other design properties should exceed the corresponding NDS WW No. 3 design values as well. With this assumption, the design characteristics of WW grade No. 3 were considered as conservative representation of PP lumber harvested from restoration programs in Southern Oregon and Northern California.

5.1.1 CLT Limitations using restoration program PP lumber

There are benefits in pooling all restoration harvested PP lumber as one class of material including reducing complexities in the production lines of engineered wood panels and maximizing the utilization. Also, it was shown that visual grading of restoration harvested PP is not sufficient to accurately sort lumber in strength classes. However, grading cannot be circumvented, because PRG-320 does not permit utilization of ungraded laminations in CLT. One alternative solution is to define a specific MSR grade for restoration program PP lumber. Although some grade-defining features such as wane, bow and twist do not influence mechanical properties, they can cause issues in the production line. Previous study on glulam beams fabricated from restoration program PP reported that presence of wane and saw skips was the major reason for rejection of laminations during the production. These exclusion criteria must be considered for CLT panels as well. Small gaps caused by wane and saw skips accelerate moisture penetration. Moreover, substantial twist in large number of laminations may be hard to overcome when pressing CLT layups. In this study, the pieces with excessive amount of bow and twist (forming about 0.5% of the material) were excluded from production of CLT panels. Despite this, our industrial partner faced an issue in clamping one of the CLT layups due to large twist produced by cumulative twist of individual pieces finger jointed together. That panel was rejected and not included in this study.

Wane does not reduce the strength of wood (FPL 2010) and it is mostly considered as an appearance factor. The main concern is that wane produce gaps between layers of CLT which accelerate moisture penetration. Planing the wane surface more aggressively compared to the other surface resolved this issue for the production of
the prototype panels fabricated at the pilot-plant, Figure X. 2 in Appendices. After such planing, it is expected that 0.5% of the material still have excessive amounts of wane which shall be excluded from CLT production.

Based on the practical experience gained from fabrication of prototype panels, it is suggested to apply the following visual limiting criteria for fabrication of CLT panels made by restoration harvested PP:

- The pieces with deep saw skips that will not be removed by planing shall be excluded.
- The pieces that have more than 5% wane area on the surface after planing shall be removed.
- Twist, crook, and bow shall be handled with care. There should be enough vertical clamping force to overcome pieces with twist and crook. Otherwise, the pieces shall be excluded. The same principle applies to bow and horizontal clamping force. Furthermore, for the lumber with twist, crook, or bow, it shall be ensured that the planer is capable of surfacing the material evenly. In other words, the thickness variations across the width of the lumber shall be within the standard range.
- There are no limiting criteria for blue stain, dead knots, resin pockets, or bore holes.

5.2 Bonding Integrity of PP CLT Prototypes

Standard bonding integrity tests including cyclic delamination and block shear tests were conducted on specimens bonded with two-component MF adhesive, Section 3. The specimens were fabricated in three scales: laboratory prototype (LP), industrial prototype (IP), and small (102 mm x 102 mm) cross-laminated blocks (BLP and JLP). The small blocks were only tested for resistance to delamination due to the fact that delamination was a persistent issue in previous studies, and it was unknown if the poor bonding was caused due to incompatibility of the adhesive with the wood species, or other influencing fabrication factors.
5.2.1 Interpretation of delamination test

BLP and JLP specimens were fabricated to eliminate the effect of thickness variations on the overall bond quality. All the specimens in BLP and JLP groups had below 5% delamination and therefore met the criterion of PRG-320. High contents of blue-stain or juvenile wood had no negative impact on the bonding performance, and it can be concluded that MF adhesive provides sufficient resistance to delamination.

Although the small CLT block specimens showed promising results, both LP and IP prototype groups, did not meet the criterion. More specifically, 3 out of 20 specimens in IP group (with maximum 9% delamination) and 4 out of 47 specimens in LP group (with maximum 15% delamination) didn’t satisfy the PRG-320 criterion. If the result were compared with the EN 16351 criterion instead, which allows for a maximum of 10% delamination, the IP group meets the criterion but LP still fails, Table 3-4.

Comparing the results, it can be assumed that the high occurrence of delamination was caused by some fabrication factors that only played a role in panel scale fabrication. Also, it is important to note that all the failed specimens in both LP and IP groups had some portion of interlaminar gaps prior to the test. It was observed that all the highly delaminated LP specimens were acquired from the center of the panels. One hypothesis is that the press tray used at the pilot-plant was not rigid enough and it might have deflected in high pressures. High thickness tolerances of laminations might be another reason for interlaminar gaps in LP samples. There was no data available for the thickness tolerances of IP sample made by our industrial partner, hence it was not possible to discuss the potential reasons for presence of interlaminar gaps in those specimens.

5.2.2 Interpretation of block shear test

Specimens in LP and IP groups passed both PRG-320 and EN 16351 block shear criteria. As mentioned in Section 1.5.1.1, PRG-320 requirements are based on average WF of all specimens, while EN 16351 specifies a 1.25 MPa minimum characteristic shear strength for all specimens, and at least 1 MPa in each glue line.
One-way ANOVA tests with 95% confidence level were conducted on the data and the results showed that there were no significant differences between IP and LP block shear results either in regard to WF or shear strength. Therefore, it can be expected that the production scale (industrial vs. pilot plant) has no significant impact on the shear resistance of the bond lines.

5.3 Structural Performance of Prototypes

The general approach was to design a custom CLT layup using a theoretical method and test prototype panels made in laboratory (LP) and industrial (IP) settings for experimental validation of the design characteristics.

5.3.1 Design of PP CLT layup

The shear analogy method was integrated in an iterative computer algorithm to design a CLT layup based on the building requirements determined in a parallel study. NDS WW grade No. 3 were used for representation of restoration program PP lamination design values. The solution derived from the algorithm revealed that a 5-ply CLT panel with gross thickness of 168 mm meets the structural requirements of the modular building designed for this project.

For the purpose of comparison, the results were compared to a E3 basic CLT grade with a similar layup, Table 4-3. E3 can be regarded as the lowest basic grade prescribed in PRG-320 that uses 1200f-1.2E Eastern Softwoods, Northern Species, or WW MSR lumber in longitudinal layers and No. 3 visual grade of similar species for transverse layers. The majority of PP CLT layup design values were lower than the E3 CLT. That is due to the fact that the design characteristics of WW grade No. 3 for all laminations (assuming random grade assignment to all plies), but E3 basic grade uses higher MSR grades for longitudinal layers, significantly increasing the overall properties. Only the shear capacity of PP CLT layup was higher than E3 CLT grade because shear strength parallel to grain (F_v) of WW grade No. 3 laminations (0.93 MPa) was higher than that of E3 laminations (0.76 MPa). It shall be noted that the
design values that PRG-320 provides for E3 laminations are different from NDS design values for any of the abovementioned species in E3 group.

Although the goal of this study was to meet the structural requirements of the building designed for this project, if needs be, it is possible to match design values of E3 basic grade by customizing the PP CLT layup even further. Matching effective stiffness is simply possible by increasing the thickness or number of plies. Also, it is possible to get close to E3 moment capacity design values by using double outer layers. Layups with a set of two parallel external layers are not very common, but are indicated as theoretical possibility in CLT Handbook (Gagnon et al. 2013) and actually fabricated by a Swiss CLT manufacturer (Schilliger Holz 2019).

5.3.2 Experimental validation of derived design values

The design values derived from shear analogy method, presented in Table 4-3, are meant for practical engineering applications. However, as per PRG-320, these values shall be experimentally validated. In other words, if the characteristic values derived from experimental tests exceed those derived from the shear analogy method, the later can be used for engineering purposes. Standard third-point and 3-point bending tests were conducted in accordance with ASTM D198 on LP and IP prototypes, Section 4.3.2. For both groups, the experimentally derived effective moment capacity, stiffness, and shear rigidity design values exceeded the predictions from shear analogy, while effective shear capacity design values were about 40% lower than the E3 grade with the same layup and the values predicted by the shear analogy method. Poor bonding quality that was discussed in Section 5.2 might be a potential reason for this low shear capacity.

It is important to note the large difference (by a factor of $x7.8$ for LP and $x7.1$ for IP) in the shear rigidity design values derived empirically compared to those predicted by the shear analogy. The source of the discrepancies might be some peculiar assumptions used in the shear analogy formulation offered in PRG-320. As discussed in Section 4.5, PRG-320 assumes $G_0 = E_0/16$ for all species, while this ratio for
clear specimen PP is about 1/7, (Kretschmann 2010), therefore, shear moduli \( (G_0) \) is significantly underestimated for PP laminations and consequently caused underestimation in the shear rigidity of the layup as well. Furthermore, this assumption implies that for lower-grades of lumber, the shear moduli decreases in a linear proportion with the reduction in elastic moduli. That assumption contradicts empirical studies suggesting that the shear modulus is independent of lumber grade (Khokhar and Zhang 2018).

Lastly, one-way ANOVA test with 95% confidence level were performed to compare the results of similar bending tests on IP and LP samples. No significant difference was found between the samples in any of the tests. Therefore, it can be inferred that the production scale (industrial vs. pilot plant) had no significant impact on the structural performance of the layup.
6

General Conclusion and Future Work
6.1 Conclusions

This section discusses the overall conclusions of this study. The general goal of this study was to assess the feasibility of utilizing restoration harvested PP lumber in fabrication of structural CLT panels for a specific type of low-rise modular building.

1. MOE distribution determined on a sample of PP lumber harvested from restoration programs in Southern Oregon and Northern California was compared with design values of commercially harvested PP lumber (WW species published in NDS supplement handbook). It was concluded that
   a. PP lumber from forest restoration thinnings assigned to visual grades No. 1 and 2 did not meet the characteristic values for their respective grades published for Western Woods in NDS supplement.
   b. All graded and ungraded groups had higher average MOE compared to Western Woods grade No.3.
   c. There were no statistically significant differences in MOE of PP lumber from restoration thinnings assigned to grades No.2, No.3, and ungraded.
   d. The marginal portion of the material graded as No. 1 had significantly higher MOE.
   e. The design values of WW grade No. 3 were regarded as provisional conservative representation of restoration program PP lumber for the practical purpose of designing CLT layups in this project.
   f. The design characteristics of restoration program PP lumber remain unknown until the full set of properties are derived experimentally and proper correlations with MOE are determined.

2. A proof of concept has been provided, showing it is possible to design custom layups using low-value Ponderosa pine lumber in all layers to meet the requirements of a certain class of low-rise modular building.
3. The prototype CLT panels using restoration program Ponderosa pine did not meet PRG-320 bond integrity criteria.
   a. While the prototype panels met the block shear criteria they failed the delamination criterion.
   b. A procedure has been proposed allowing successful separation of adhesive compatibility from other fabrication factors. The procedure allowed us to eliminate adhesive compatibility as a potential cause of the delaminations.
   c. MF adhesive system was found compatible with restoration program Ponderosa pine regardless of high presence of blue-stain and juvenile wood.
   d. Delaminations were observed in the CLT panels were tracked to pre-existing interlaminar gaps in both samples.
   e. The specific source of interlaminar gaps could not be determined, but in case of pilot plant sample evidence point at thickness tolerances or uneven clamping.
   f. No evidence was available for industrial plant sample.

4. Experimentally derived flatwise characteristics of the CLT prototypes using restoration program Ponderosa pine were determined.
   a. All tested flatwise characteristics were higher than the requirements of the target modular building.
   b. Also, except for shear capacity, the experimentally derived values including effective moment capacity, stiffness, and shear rigidity were higher than shear analogy estimates based on design values for visual grade No. 3 for Western Woods.
   c. Shear analogy method considerably underestimated effective shear rigidity compared to the respective design value derived experimentally. The reason may lay in some peculiar assumptions used in the formulation of shear analogy method offered in PRG-320.
   d. A proof of concept has been provided demonstrating that Ponderosa pine lumber obtained from logs harvested in SW Oregon and Northern California
forest restoration programs can be utilized in project-specific CLT grades for a certain type of low-rise building, provided the technological issue leading to delaminations is identified and solved.

e. Out of plane characteristics of the CLT grades were not studied in this project.

f. No significant difference was found between performance characteristics determined on panels produced in pilot-plant scale and industrial scale lines.

6.2 Future Work

Future work should focus on:

- Determine design values of Ponderosa pine lumber obtained from logs harvested in restoration programs in SW Oregon and N California. Derive the correlation between MOE and MOR for definition of a new MSR grade in order to unifying the classification of restoration program PP lumber.

- Diagnose the fabrication factors that cause interlaminar gaps and large delaminations despite the compatibility of the adhesive with the species, in order to eliminate those issues.
7

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https://doi.org/10.1016/j.conbuildmat.2020.120168

BS EN (2015) EN 16351 Timber structures - Cross laminated timber - Requirements

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Appendices
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7.1 Appendix A: SOP CLT fabrication

The specific purpose is to elaborate on the procedures used for fabrication of Ponderosa pine Crossed Laminated Timber (CLT) at Emmerson lab pilot-plant. Also, this document is established as a guideline for future students who want to fabricate CLT in the same environment.

This document does not replace any specific training for the equipment, but only shall be used as a technical note for the production procedure.

7.1.2 Required Personal Protection Equipment (PPE)

- Safety goggles, protective gloves, lab coat, masks, hard hat.
- Hard toe shoes are required for all stages of the production.
- A person overseeing the safety of the operator (safety buddy) is needed.
- Must complete lab safety training as well as training for the equipment mentioned below.
7.1.3 Process equipment and materials

Planer Machine (training needed), Table saw (training needed), Forklift (training needed), Minda Press (training needed), Henkel Adhesive Applicator (training needed), Cart, Weighing scale (0.01g accuracy), Sticky notes, Caliper, Measuring tape, Two-component (resin and hardener) adhesive, Dimension lumber (process at least 6 extra boards)

7.1.4 Instructions

The first task is to determine the size of the CLT panel desired. This can be calculated based on the number and dimension of specimens that shall be acquired for the specimens. A 76 mm (3 in.) off-cut margin may be considered on all 4 edges of CLT. The maximum dimensions of the panel is limited by the size of the Minda press which is 2.43 m by 3.05 m (8 ft by 10 ft).

7.1.4.1 Cutting the lumber

Depending on the size and number of plies of the desired CLT panel, the lumber (laminations) shall be cut to the size. The length of longitudinal laminations shall be equal to the length of the desired CLT and the length of transvers laminations shall be equal to the width of the CLT panel. If side pressure is desired, the length of the plies that pressure is being applied to shall be longer than the neighboring plies, Figure X. 1.

Figure X. 1, increased length of plies to make application of side pressure possible.
Safety Notes: Wear safety glasses and ear protection. Make sure that you have easy access to the emergency turn off. Never use gloves while working with the saw, although you can use gloves for the purpose of stacking lumber.

7.1.4.2 Planing (surfacing)

Planing shall happen within 48 hours of CLT fabrication. The goal is to refresh the surface of material for good bonding and reduce thickness variations. Using caliper, get an estimation of lumber thickness on different locations of about 10 specimens. This is important because unplanned lumber usually have large thickness variations. To make sure all surfaces were touched by the planer, an estimation of minimum thickness is needed. Figure X. 2 shows the layout of the planing area. Accumulate the boards on a cart or on ground on the feed-in side of the planer. One person shall be responsible for feeding in the lumber, another one shall stand on the other side to receive and stack the lumber. Please note that the lumber shall be fed to the device horizontally, so that the amount of material removed from the ends are the same as the middle. The same as feed-in, the lumber shall be received horizontally on the output side. Installing a roller table might help with that. Turn on the device and start feeding in. Be cautious that the lumber can move only in feed-in direction. In other words, when the lumber hits the blades, they cannot be pulled out anymore.

Figure X. 2, planing the lumber for fabrication of CLT.
As shown in Figure X.2, it is beneficial to plane the wane side of the lumber more aggressively to eliminate the wanes as much as possible. This is also true for pieces with saw skips on them.

Also, make sure to schedule with laboratory manager and reserve the working area ahead of time. Working with the planer requires a large space and the access to nearby equipment will be limited.

Furthermore, planing lumber produces a lot of saw dust. Thus, check the dust collection system frequently to make sure that it has not been overfilled.

**Safety Notes:** Use leather gloves. Wear safety glasses and ear protection. Make sure that you have easy access to emergency turn off, Choose a large working area.

7.1.4.3 Preparing adhesive applicator

Read the adhesive manufacturer’s manual and select the appropriate spread rate ratio depending on the environment temperature and desired press time. Calculate the amount of resin and hardener needed. Considering the unavoidable adhesive waste during production, double the amount. Pour the resin and hardener in the adhesive applicator’s compartments accordingly and turn on the pumps on low power, Figure X.3. Wait until there is a uniform flow from all bids. If the resin is too viscous to flow, it might help to warm up the resin (refer to manufacturer’s manual for allowable temperatures). Make sure that the resin and hardener does not cross contaminate in any stage of the production, or else it will severely damage the applicator.
To achieve the desired spread ratio the motor power of the applicator and speed of the conveyer belt shall be adjusted accordingly. A simple technique is to place a sticky note on a piece of lumber and let it pass on conveyer belt through the applicator. For this, measure the dry weight of sticky notes first and then turn on the motor to pour either resin or hardener at a time. After the resin or hardener is applied, gently remove the sticky note from the lumber and weight it again. By having the dry and wet weight of the sticky note, as well as the surface area of the sticky note it is possible to calculate the current spread rate. The spread rate can be changed by either changing the speed of conveyer belt or the power of motor (flow rate). Repeat this procedure as many times as needed to achieve desirable spread rate for both resin and hardener.

**Safety Notes:** Wear mask, nitrile gloves, mask and lab coat. melamine formaldehyde adhesive is water soluble. If spilled wash with warm water.

7.1.4.4 CLT assembly

It is helpful to count how many pieces are needed for each ply and stack the longitudinal and transverse pieces layer by layer on the feed-in side of the conveyer belt. Note that adhesive is only applied to one side of the laminations, hence the top-most lamination requires no adhesive, therefore it can be stacked beside the press for easy access.
Turn on the conveyer belt and adhesive applicator’s motors and feed in the lumber one by one. One person shall stand on the feed-in side and two people shall receive the pieces on the other side and assemble them on the tray of the press, Figure X. 4. Since the person standing on the feed-in side have limited vision on the assembly side, it is important to establish a sign communication system between groups so that the person knows when they are ready to receive the next piece.

![Image](image_url)

*Figure X. 4, Feeding the lumber to the adhesive applicator and assembling laminations.*

Adhesive is applied to the top surface of lumber, therefore, all pieces shall be placed faced up on the press tray. Starting from the bottom ply, assemble each layer and go to the next. Note that the top-most lamination does not require adhesive and shall be assembled dry. Once the assembly is ready, push the tray back in the press.

**Safety Notes:** Wear mask, nitrile gloves, mask and lab coat. melamine formaldehyde adhesive is water soluble. If spilled wash with warm water.

7.1.4.5 Pressing

Refer to Minda’s manual for operation guidance.

If side pressure is desired, first lower the vertical cylinder down so that the top clamping plate touches the layup but only a minimal vertical pressure is applied. The purpose is to limit the space so that laminations don’t pop out when vertical pressure is applied. Then you can apply the side pressure (horizontal), and later fully apply the
vertical pressure. If the vertical pressure is applied first, the friction between clampint plates and the layup will counteract the side force.

Let’s say the full press duration is 3 hours based on the adhesive manufacturer’s guideline. After this 3 hours, the bonding is not fully stable yet and impacts might damage the bonding. It is recommended to follow the press time by curing time (typically 24 hours). During this, the panel shall be handled with care and also the panels are typically subjected to reduced pressures. This can happen either by placing the panels underneath deadload (stacking panels for example) or keeping them in the press with reduced pressure (about 1/6 of the original pressure).

Once the panels are cured, a forklift or crane can be used to move the panels.
7.2 Appendix B: SOP CLT Delamination Test

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**Department of Wood Science and Engineering**

**Oregon State University**

**SOP: CLT Delamination Test**

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<th>04/24/2019</th>
<th>Authors: Sina Jahedi</th>
<th>Pages: 5</th>
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7.2.1 Objectives

Delamination test is one of the primary tests required to certify a CLT layup using a specific type of adhesive. ANSI/APA PRG-320 refers to AITC T-110 standard for this test. The objective of this standard operation procedure is to technically describe the steps required for specimen fabrication and testing for cyclic delamination. This document was established as a guideline for future WSE students. Furthermore, the procedures are targeted for the equipment available at Highbay, Richardson Hall.

*This document does not replace any specific training for the equipment, but only shall be used as a technical note for the testing procedure.*

7.2.2 Required Personal Protection Equipment (PPE)

- Safety goggles, ear muffler.
- A person overseeing the safety of the operator (safety buddy) is needed.
- Must complete lab safety training as well as training for the equipment mentioned below.
7.2.3 Process equipment and materials

CLT specimens, Band saw or Table saw (training required), Vacuum vessel (training required), Measuring tape, SI ruler with mm increments, Camera, microscopic camera or magnifying glass, Chisle, Weighing scale (0.1g accuracy).

7.2.4 Instructions

7.2.4.1 Specimen preparation

Based on the standard, the final size of the specimens shall be 76 mm by 76 mm (3” by 3”), and at least three specimens shall be acquired from three locations across each panel (two corners and one center). Use band saw or table saw to cut the specimens. The thickness and number of plies of the specimens shall remain the same as the original panel.

Record the weight of several specimens before starting the dry-wet cycle. Also, check all of the specimens for any pre-existing interlaminar gaps. Mark the interlaminar gaps and record the length for analysis. Measure and record the moisture content of the specimens.

**Safety Notes:** Wear safety glasses and ear protection. Make sure that you have easy access to emergency turn off. Never use gloves while working with saw, although you can use gloves for the purpose of stacking lumber.

7.2.4.2 Saturating the specimens with moisture

Make sure the vacuum vessel is empty and none of the water valves are obstacle, Figure X. 5. Place the specimens in a bag that allows water transmission (e.g. net or cloth bag). The faces of CLT blocks shall not fully cover each other. This is to ensure that water penetrates to all specimens without any obstacle. Place the bag in the vessel. Circular weights are located beneath the vessel. Place them on top of the specimens to make sure that the bag fully submerge and won’t float on top. Close the lead of the vessel and tighten the bolts evenly on all sides.

Attach the water hose to the valve below and start filling the vessel with water. Leave the top 20% of the vessel empty so that there is enough room for air compression.
Once the vessel is filled with water, close the water valve. Then attach a hose from the high-pressure air supply system to the valve of the vacuum device located on top of the vessel.

![Figure X. 5, Delamination specimens placed in the vacuum vessel.](image)

Slowly open the valve and apply a 0.85 bar (12.3 psi) vacuum for 30 minutes. Release the vacuum and remove the air hose and attach it to the pressure valve. Apply a pressure of 5.2 bar (75 psi) for two hours in order impregnate the specimens with water. Check the pressure frequently in the first 20 minutes to make sure that the pressure is consistent.

**It is important** to read the pressure gauge to make sure 1) the vacuum is fully released before applying pressure and 2) there is no air pressure in the vessel before opening it. Furthermore, apply pressure gradually. Sudden changes in pressure can damage the specimens. The same thing applies to releasing the pressure.

**Safety Notes:** Wear safety glasses and ear protection. Releasing the air pressure from the vessel makes a very loud noise.

7.2.4.3 Drying cyclic

The specimens shall be dried to 110-115% percent of their original weight within 10-15 hours at a constant temperature of 70 degrees of Centigrade. The green oven at the Highbay has such capacity. Place the specimens in the oven and give a 5 cm space
between the specimens in order to facilitate the air flow, Figure X. 6. Turn on the oven and let the specimens dry for almost half a day.

**Hazard Note:** Double check the temperature of the oven. If the temperature is above 100 degrees of Centigrade, the specimens might start burning.

![Delamination specimens placed on the oven for the dry cycle.](image)

After 10 hours open the oven and select the specimens that you have their original weight recorded and weight them again. If the weight is within 110-115% of the original weight, then you can start assessing the delamination, otherwise let the specimens dry further.

### 7.2.4.4 Delamination assessment

Set up a camera to take pictures from all four sides of the specimens immediately after taking the out of oven. Inspect the specimens and mark the delamination gaps by a sharpie. Measure the total length of delamination by a ruler and record the data. The delamination gaps start closing while the specimens are cooling down, that is why it is best to take three specimens at a time from the oven. Also, it is helpful to use a microscopic camera, or magnifying glass for identification of delamination gaps, Figure X. 7.
7.2.4.5 Data analysis

Sum of length of delaminated areas is measured and shall be reported as a percentage of the sum total of bond line lengths. PRG-320 requires that all of the specimens within a group shall have less than 5% delamination, otherwise the whole group has failed.

Chisel test might help with identifying the potential causes of delamination. Using a chisel and a hammer, break the delaminated specimens to investigate the bonding, Figure X. 8. It is possible to estimate the percentage of wood failure from looking at the bonding surface.
Figure X. 8, Chisel test.
7.3 Appendix C: SOP Block Shear Test

Department of Wood Science and Engineering
Oregon State University

SOP: CLT Block Shear Test
Pages: 4

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7.3.1 Objectives

As a part of bond integrity tests, block shear is mandated by PRG-320 which refers to AITC T-107 standard for this test. The objective of this standard operation procedure is to technically describe the steps required for specimen preparation and testing for block shear. This document was established as a guideline for future WSE students. Furthermore, the procedures are targeted for the equipment available at Highbay, Richardson Hall.

*This document does not replace any specific training for the equipment, but only shall be used as a technical note for the testing procedure.*

7.3.2 Required Personal Protection Equipment (PPE)

- Safety goggles, ear muffler.
- A person overseeing the safety of the operator (safety buddy) is needed.
- Must complete lab safety training as well as training for the equipment mentioned below.

7.3.3 Process equipment and materials

CLT sample, Band saw (training needed), Caliper, Instron universal testing machine (training needed), Block shear test mount.
7.3.4 Instructions

7.3.4.1 Specimen preparation

Figure X. 9 provides the shape and size of block shear specimens as described in AITC-T107. Use band saw to cut the CLT sample into block shear specimens. It is more time efficient to cut the CLT sample into small cubic blocks first, and then cut the steps in the next round.

*Figure X. 9, shape and size of block shear specimens.*

*Figure X. 10, an example of a poor cut for block shear specimens.*
Note that the specimens shall be cut exactly on the bond lines with a sharp angle in the stair steps. Figure X. 10 shows an example of a poor cut. As a sign of good cut, the adhesive should be partially visible on the stair step (if not transparent).

7.3.4.2 Test setup

Install the block shear mount on the Instron universal testing machine located at RH 174, Figure X. 11. There is no need to fixate the bottom anvil shaped mount to the Instron machine, as it is heavy enough to stay in place. Use the appropriate pins to connect the moving plate of the mount to the Instron’s frame. Pay special attention to the alignment of the moving plate with the grip on Instron, so that they shall slide freely on the vertical direction.

Open the Bluehill software and select the block shear test module. This test can be found among the compressive tests. Ensure that the head speed is assigned to 12.7 mm per minute. Refer to the Bluehill manual for training on how to use the software and record test data. Only the ultimate load is needed for the analysis and the records of the displacement are not necessary but might be useful for analysis.

7.3.4.3 Testing procedure

Mark the specimens with ID. Each bonding surface shall be tested separately, so it is necessary to mark bonds as well. Use caliper to measure the length and width of each bonding surface. Inspect all surfaces for any pre-existing interlaminar gaps. Mark the
interlaminar gaps and measure the total length. Measure and record the moisture content of the specimens.

Figure X. 12 demonstrates the assembly of the block shear specimens in the testing apparatus. It is important to ensure that all surfaces of the stair step are in direct contact with the testing apparatus. If needs be, place a spacer to fill the empty gaps.

Figure X. 12, A block shear specimen ready to be tests.

Tare the load cell before the test. Bring down the moving plate until it touches the specimen (load increases to about 60N). Run the test and wait until the specimen break. Record ultimate shear strength value, ID of the specimen and bond line, and repeat for the next bond.

7.3.4.4 Wood failure assessment

Refer to the SOP: Determination of Wood Failure Percentage Using ImageJ.

7.3.4.5 Data analysis

PRG-320 block shear criteria are: 1) at least an 80% average of WF in all specimens and 2) a minimum of 60% WF in each specimen. Each bonding plane have two sides, select the minimum WF percentage of the two sides as the WF of that bonding surface. Calculate the average WF in all bond planes. Report the average WF of all specimens and compare with the criteria.
Although shear strength is not a criterion for bond integrity tests in PRG-320, it can help with further analysis of the data. Also, it might be beneficial for the analysis to record the mode of failure, i.e. rolling shear or shear parallel to the grain.
7.4 Appendix D: SOP Determination of Wood Failure Percentage Using ImageJ

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<tr>
<td>08/22/2018</td>
<td>Authors: Warren, Matthias Kleissl, Sina Jahedi</td>
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7.4.1 Objectives

Wood Failure (WF) is a measure to compare the bonding strength to the rupture of wood fibers. WF is expressed in percentage as the ratio of the area of wood fiber remaining at the bond line to the total bonding area involved in the test. Determination of WF percentage in block shear specimens is mandated by PRG-320. Refer to SOP Block Shear Test for more details on the PRG-320 bond integrity criteria.

The objective of this standard operation procedure is to technically describe the steps required for WF assessment using a specific image processing tool and provide a guideline for future students. While there are various techniques for WF assessment, the focus of this SOP is limited to image processing with ImageJ.

7.4.2 Required Personal Protection Equipment (PPE)

- Safety goggles, protective gloves.
- Must complete lab safety training as well as training for the equipment mentioned below.
In the UV room it is required to wear safety glasses as the UV light can affect the eye vision in both long- and short-term exposure. Protective gloves should be used if the glue is a toxic.

7.4.3 Process equipment and materials

Camera (SD Card), Tripod, Light source (UV or natural – wavelength depends in the type of adhesive used), tested block shear specimens.

7.4.4 Instructions

The general approach is to capture images from the bonding surfaces with a specific light wavelength that shows high contrast between adhesive and wood fibers, and then import those images in an ImageJ script to calculate the WF percentage. For the purpose of capturing images, it is best to use VSC8000/HS digital imaging and multi-wavelength illumination device, Figure X. 13. This device is equipped with a high-resolution camera and built-in adjustable lights to cover a large spectrum of wavelengths.

If the device is not available, similar procedure can be replicated by following the instructions presented in Section 7.4.4.1.
7.4.4.1 Setting up a photo shooting area

Clean up the darkroom (Richardson Hall 173) and remove everything from the table. Use clamps, wood and a background to build a photo-shooting, Figure X. 14. Having a stable setting extremely helps with time efficiency. Moreover, since the picture frame is fixed, all photos can be cropped automatically. Set up the camera on a tripod and fixate it. Set the camera on “super close-up” or similar mode. **Important:** Go to the camera setting to fixate the lens focus, shutter speed, and apparatus exposcer. In other words, turn off the auto adjustments option on the setting. This is highly important because all of the photos shall be comparable to each other. Also, ensure that the camera is not applying any filters to the images.

If the adhesive is transparent, UV lights shall be used to illuminate the surface. Try different wavelengths of UV light to find the one that demonstrates the highest contrast between wood and adhesive. Usually, adhesive shines brighter under UV light which can be used as an indicator for WF assessment.

![Photo-shooting Setup](image)

*Figure X. 14, Photo-shooting Setup.*

7.4.4.2 Analysis with ImageJ

Download and install the ImageJ software. Access the image processing script named as “Threshold Action Script.txt” in the GitHub repository linked below:
**Source Code Repository:** [https://github.com/sina-jahedi/Wood-Failure-Image-Processing](https://github.com/sina-jahedi/Wood-Failure-Image-Processing)

Save the Notepad file as .txt (not .js or other). Open ImageJ and drag and drop the saved script into the program. Press Ctrl + R to run the script. The application will prompt you to select a folder to store the analysis results in and then asks for the folder where the initial block shear images are stored in. Once selected, the application reads all of the images in the folder and prints the WF percentage detected in each image on a separate .txt file named the same as the original image.

![Images](https://example.com/images)

**Figure X.** 15 Images captured from bonding surface of block shear specimens and the processed image after passing through contrast threshold.

As mentioned previously, it is best to use exactly the same frame so that all of the pictures can be cropped automatically. The provided script crops all images with the same margin. To change the crop size, open the “Threshold Action Script.txt” file and change the values specified in line 23. Width and height indicate the size of the cropped image while x and y indicate the coordinates of the original image to be cropped from.

Furthermore, it is possible to change the default threshold by changing the values in line 48 and 49 of Threshold Action Script.txt” file. To tune the threshold for the most
appropriate value, compare the results achieved from ImageJ (areas identified as adhesive are painted in red) with real life specimens.

The ImageJ script prints the results in separate .txt files. A Python script “read_files.py” was developed to automate the process of reading the results and prints all results in one unified file named “summary.csv”. To run this script, the script shall be stored on the same directory level as “results” folder. You need to have Python installed on your machine.

The current Python script is designed in a way that sorts and prints the left side and right side WF assessment of a bondline. To use this functionality, you shall name the pictures (and consequently the result files) in a specific format. The last character in the picture names indicates whether this image belongs to the left side of the bond line (L) or the right side (R). For instance, the image “A03L.jpeg” is the left side of the bonding line A03 and “A03R.jpeg” is the right side.
7.5 Appendix E: Documentation for The CLT Design Values Calculator Application

A Python script was developed to calculate the design values of a given CLT layup based on shear analogy method. The software accepts arbitrary properties of the laminations as well as characteristics of the CLT layup, e.g. thickness, number of plies, etc. and calculates CLT design values in the minor and major directions. A second script was developed to optimize the layup in a reverse sequence of initial algorithm, meaning that, it calculates the most suitable CLT layup based on a given set of desired design values for the CLT.

Shear analogy method (Kreuzinger 1999) assumes that the panel is made of two virtual beams connected with rigid links. Beam A has the “inherent flexural and shear stiffnesses on individual plies along their own centers” and beam B considers the “increased moment of inertia due to distance from the neutral axis”. The effects of shear deformation are considered in this methodology. PRG-320 Appendix X3 provides a formulation for shear analogy method which was followed precisely in the development of this application. Any assumption used in PRG-320 is also applicable to this application. Refer to the standard for details of the formulation.

The input properties for lamination can be acquired from experimental tests or previous studies. National Design Specification (NDS) supplement handbook provides the lamination design values for commonly used visually graded dimension lumber in Table 4A. The design values of Western Woods Grade No.3 were used for both longitudinal and transverse laminations in this project.

For the sake of conserving space, the script along with a detailed documentation on how to use the application are uploaded on an open-access GitHub repository linked below:

**Source Code Repository:** https://github.com/sina-jahedi/CLT_Design_Values_Calculator