AN ABSTRACT OF THE THESIS OF

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Title: Utilization of Low-value Lumber from Small-diameter Timber Harvested in Pacific Northwest Forest Restoration Programs in Hybrid Cross Laminated Timber (CLT) Core Layers: Technical Feasibility

Abstract approved:

Lech Muszynski

Each year the United States: Forest Service (USFS) spends billions of dollars fighting forest fires. One strategy used by the USFS to prevent catastrophic fires is through forest restoration programs, in which potential forest fuel is removed through mechanized thinning. This program is expensive and generates high volumes of small-diameter logs (less than 6” at the small end). This material is often converted to low-value wood chips, pulp, or biomass. Some of these small-diameter logs can be processed in local specialized sawmills capable of processing it into lumber. What is not utilized locally from the restoration programs, is transported at a cost to the USFS to the nearest facilities that can use or process the produced products from the thinning. Creating a value-added product using low-grade lumber produced from small-diameter timber would improve the economic balance for forest restoration operation.

The general aim of this research was to increase or stimulate markets for wood products utilizing low-value small-diameter material generated in National

Forest System restoration programs. Our hypothesis is that low-value lumber cut from small-diameter logs (4”-6” at the small end) could be successfully utilized in core layers of structural cross laminated timber (CLT) panels. Cross -laminated timber is an engineered wood panel composed of solid-sawn lumber, such as 2x6 or 2x8, laid up in perpendicular directions and used as prefabricated walls and floors.

However, to be qualified for structural uses, CLT must meet standard minimum bond integrity criteria specified by the North American product standard (ANSI/APA PRG 320-2012), determined through laboratory testing for delamination (≤5%) and shear resistance (≥80% wood failure).

The objective of this project was to determine the feasibility of small-diameter logs harvested from National Forest System restoration programs in 3- and 5ply CLT panels. Adding value to low-value timber harvested from USFS lands by using it within CLT applications is expected to increase profitability of the harvested timber, offsetting costs for the restoration programs.

The specific objectives were to: (1) build and test CLT panels utilizing lumber from forest restoration operations in core layers of panels against the certification criteria per PRG 320-2012 to allow low-grade lumber in cores of structural CLT; (2) based on findings, propose respective changes to the current North American standard PRG 320-2012; and (3) investigate the efficiency of the primary processing of small-logs from the thinnings and lamination options with lumber produced from these small logs.

The approach was to incorporate the forest restoration material harvested in the larger Pacific Northwest region into the cores of 3- and 5-layer hybrid CLT panels and assess the technical viability of these panels by testing layup samples against the standard adhesive bond integrity criteria, and by comparing the characteristic engineering properties of the material (E, MOR, and rolling shear) with the standard CLT grade benchmarks. All tests were performed following the standard test protocols of the ANSI/APA PRG 320-2012.

Blue Mountain Region of Eastern Oregon, and the Fremont-Winema forest in Southern Oregon were selected as representative forest restoration sites. The species harvested were Ponderosa pine, White fir, and Douglas-fir. The small logs processed at Idaho Forest Group (IFG) Lewiston, ID facility mainly produced a nominal 2x4, mostly No.2 & BTR visual grade lumber; Collins Co. donated Utility grade 2x4s. The 3- and 5-layer hybrid test panels were manufactured at D.R. Johnson in Riddle, OR consisting of No. 2 visual grade Douglas-fir as the panel's faces and mixed species from the restoration thinnings in the core layers. The hybrid panels were used to determine E and MOR (f_b) using third-point bending, rolling shear (f_v) through center-point bending, as well as adhesive bond integrity via block shear and cyclic delamination tests.

In addition, 3- and 5-layer homogeneous panels consisting of Ponderosa pine, White fir and Douglas-fir were produced to detect and separate the potential effects of individual species on the adhesive bond integrity in the layups with mixed species in the core. These homogeneous panels were only used to determine the rolling shear strength in the core layers and to evaluate the integrity of the adhesive bonds. Homogeneous Douglas fir laminations constructed with standard lamstock used in commercial CLT production at DR Johnson were used as control material.

The efficiency of primary and secondary manufacturing processes was also evaluated by company interviews and on-site visits.

The control sample group, the homogeneous 3- and 5--ply No.2 visual grade Douglas-fir, met the minimum qualifications for the PRG 320-2012. The CLT test panels incorporating mixed species material from forest restoration programs in the core layers have shown good strength and elastic properties (compared to the standard E3 pre-defined CLT grade). However, in contrast to the reference commercial all Douglas-fir panels, none of the CLT panels with mixed species material from restoration programs passed the delamination test for bond integrity. Of the additional homogeneous layups, only 3-ply White fir combination passed the delamination test.

Potential causes of failure might have been related to processing issues: 1) inconsistent thickness tolerances of laminations and 2) incompatibility of species-specific adhesive system with the species mix used in the tests.

In the light of the current findings, none of the sample groups with material from forest restoration programs qualified for structural CLT per PRG 320-2012 standard criteria.

Further investigation is needed to identify factors affecting the delamination failures, which both appear to be related to the manufacturing process and, thus, possible to mitigate.

Regarding the efficiency of production of lumber and CLT panels from small logs, additional presorting during harvesting and mill processing steps may help increase process efficiencies during breakdown manufacturing steps. The efficiency of the IFG primary saw line was substantially lower when processing logs of diameters below 6 inches at the small end than normal production; however, with increased familiarity of the project's thinned material, production efficiency should increase through additional pre-sorting and machine system settings.

The economic feasibility side of using the harvested material conducted by Lawrence (2017), who found the material to not have significant to persuade CLT manufactures in the use of the material (Lawrence 2017).

Utilization of Low-value Lumber from Small-diameter Timber Harvested in Pacific Northwest Forest Restoration Programs in Hybrid Cross Laminated Timber (CLT) Core Layers: Technical Feasibility

by
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APPROVED:

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Dean of the Graduate School

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

Christina Lawrence, Author

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CHAPTER 1: INTRODUCTION

1.1Fire suppression and prevention in Pacific Northwest forests

Forests in the Pacific Northwest are prone to catastrophic fires (Climate Central 2012). These fires are typically caused by lightning, debris burning, equipment usage, and other human activities (ODF, 2017).

Since 2000, national federal firefighting costs for suppression alone has averaged over $1.4 billion annually; at its peak in 2015 it cost well over $2.1 billion (National Interagency Fire Center 2017). By some estimates, this number could drastically increase by the year 2050 (Geiling 2015). However, other fire management options, other than suppression, have been studied over the years. Backer et al. (2004) noted:

> "In a system of fire management that attempts to weight the costs of fire suppression against potential losses due to fire, the ecological cost is often not acknowledged, despite the fact that adverse effects from suppression activities may be substantial and persistent and in some instances, may exceed impacts attributable to fires themselves."

The damage of an area's ecosystem due to catastrophic fires may have long-term undetermined consequences.

1.2 Forest restoration programs

One of the strategies used to prevent catastrophic fires is forest restoration program. The National Forest System restoration program uses selective timber harvesting and forest thinning other methods to remove smaller trees and forest fire fuels from a specified area or land plot. Federal forests are subject to stewardship contracting for such treatment, which are developed collaboratively to give social license for forest operations. These contracts help to achieve land management goals within an area and can last up to 10 years (USDA 2009).

When contracting out stewardships the USFS makes it clear as to which trees are to be harvested, determined by the species, log sizes and other factors targeting smaller trees results in large volumes of small diameter logs (less than 6 inches at the small end). This is to help preserve the type of ecosystem that has been determined to be most fit for an area and improve its resilience. Additional benefits of the restoration programs are positive effects on tree growth rates, species composition, resistance to insects and disease, and wildlife habitat quality (Parker and Bennett 2005). However, due to long yarding and haul distances the forest restoration programs are expensive (Rainville et al. 2008a) and must compete for funding with the increasing demand for fighting forest fires every year. The revenue from the sold/removed materials does not offset the costs and thus pace and scale of restoration need to be subsidized by the USFS due to the limited economic value of restoration challenges projects.

1.3 Current use for thinning material

The timber harvested for National Forest System restoration projects is thought to be low-value because the projects target smaller trees often of lower quality unlikely to produce many commercial logs (Rainville et al. 2008b).

For best efficiency of lumber production, and to produce the least amount of waste, many lumber mills decline to process logs less than 6 in. at the smaller end and deem them as unprofitable. Therefore, currently the typical use of the thinning material is in residual products (chips, pulp, and biomass) and its commercial value is quickly diminished by the transportation costs between the treatment area and the nearest processing plant (Lawrence 2017).

In recent times however, improved technology has led to increase efficiency of production at sawmills throughout the Western United States and some mills in the region now specialize in processing smaller logs and less valuable trees (Blatner et al. 2013). It is reasonable to assume that this trend will continue, and that in the future there may be more mills capable of processing small-diameter logs, including these generated in forest thinning operations in the region. One way to better offset costs of forest restoration and thinnings is to find a value-added outlet for the material generated in these operations. One of such potential outlets is the cross-laminated timber (or CLT) technology.

1.4 Hypothesis

The main hypothesis of this study was that the small diameter logs generated in forest restoration thinnings could be used in Cross Laminated Timber (CLT). CLT, which is a new building material that has been growing in popularity in North America.

CLT is a structural composite panel product usually consisting of 3 to 9 layers of dimension lumber arranged perpendicular to each other (Figure 1), much like layers of veneer in plywood, and can be used as a prefabricated wall, floor and roofing element in residential, public and commercial structures.

We anticipate that this low-value lumber, harvested from small diameter timber, may be utilized in the core layers of CLT panels. The ability to use low grade lumber in CLT may create additional market outlets to utilize the lumber produced from restoration material. Additional market outlets for low value material, would support additional revenue to further pace and scale of restoration, while providing the CLT manufacturers with raw material at a lower cost. This hypothesis is based on the emergence of sawmills specializing in processing small diameter logs and the emergence of the CLT industry in the region.

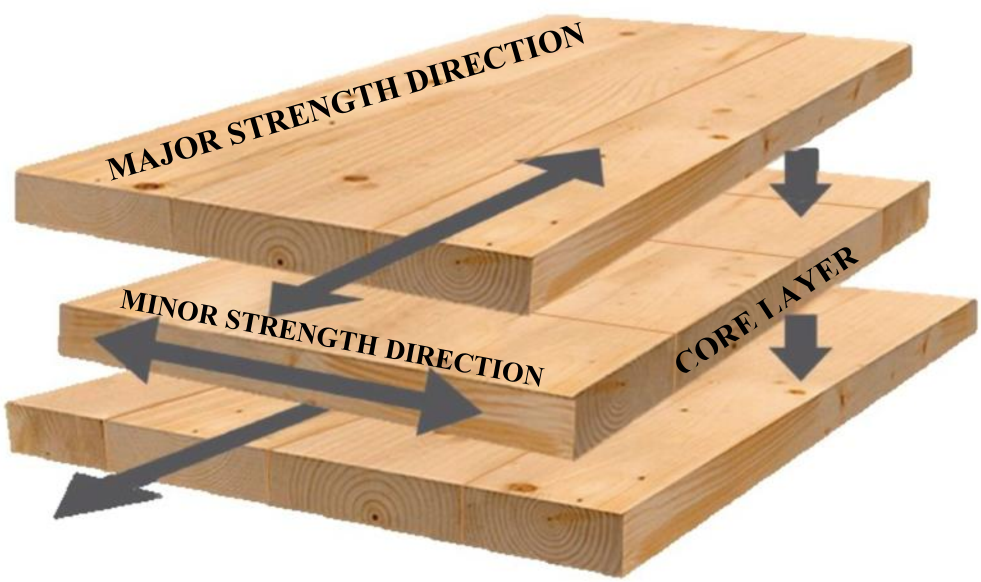


Figure 1: Example of the standard cross laminated timber lay-up.(Laguarda Mallo and Espinoza 2015)

1.5 Problem statement

To decide whether material generated in forest thinnings and restoration operations in federal lands could be used for CLT, the following questions must be asked:

1. Will CLT panels with this material in the cores be technically viable? That is, will they meet the CLT product standard criteria?

and

2. Would utilization of the forest thinning material in CLT cores be commercially viable? Assuming the density of CLT operations and sawmills capable of processing small logs in the region will continue to increase.

The technical viability and the potential for utilization of low quality of lumber processed from small diameter logs (i.e. presence of juvenile wood, high knot content, and cross grain) in CLT has to be investigated. Concerns related to the commercial viability include: matching the projected volumes of small diameter lumber generated in the restoration operations measure to the projected capacity of the CLT industry in the region and the effect of the regional logistics and processing efficiencies on the commercial viability of this path of utilization.

The general goal of this project was to determine the technical, or mechanical, viability of utilizing small diameter (small-end diameter of 3.5”- 6”) logs within structural CLT products. The important context of this investigation is the use of state-of-the-art in manufacturing technology and the product standard used to qualify CLT products for structural uses.

1.6 CLT technology

The ANSI/APA PRG320-2012 product standard defines Cross-laminated Timber as “a prefabricated solid engineered wood panel made of at least three orthogonally bonded layers of solid-sawn lumber or structural composite lumber (SCL) that are laminated by gluing of longitudinal and transverse layers with structural adhesives to form a solid rectangular-shaped, and plane timber intended for roof floor, or wall applications” (ANSI 2012). The multilayer structure of the panels allows stress to be redistributed between the layers in such a way that lower quality lumber may be used in the center layers of the panels where compression and tension stresses are not the highest.

The CLT Handbook identifies shear strength and stiffness as key issues that can control the performance and design of both the floor and wall systems (FPInnovations and Council 2013). In CLT elements subject to bending (floor and roof assemblies) the normal stress is carried by the face layers while the core layers contribute by transferring the shear load between faces.

In CLT the cross-laminated layers result in elastic properties alternating representation of the displacement and strains in accordance with the orientation of lumber. A diagram explaining the distribution of the stresses occurring within the panels can be seen in Figure 2 (Brandner et al. 2016).

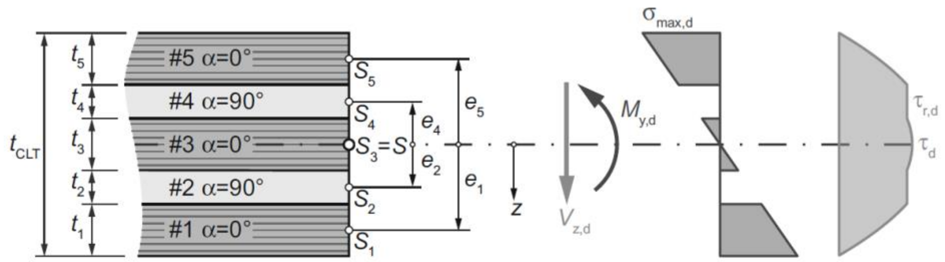


Figure 2: Normal and shear stress distributions across the thickness of 5-ply CLT plates. (Brandner et al. 2016)

In Figure 2, in-plane shear stress pattern is calculated for a cross section of a 5-ply CLT panel. The observation that laminations in core layers experience low levels of stress along the grains and that the shear strength properties in lumber known to be independent of the grade (Hochreiner et al. 2014; Grandyuinet and Muszynski 2016; Gupta et al. 2004) it is possible to propose that CLT may allow for the use of grades of lumber lower than specified in the product standard in the center layers (ANSI 2012). This could create an outlet for this low value lumber from restoration programs. The idea of using a lower grade of lumber within the core of the panels is not a new concept to the engineered wood products industry, as it has been utilized within glue laminated (glulam) products (AWP 2015), where lumber is laid parallel to each other to form a large beam member.

The CLT manufacturing process and the construction technology based on this product has been developed in Europe over the last 20 years despite the lack of a product standard. The first European CLT standard was drafted in 2011 (prEN16351 2011) (Williamson 2017) and the most recent version was updated in 2015 as EN-16351 (EN 16351 2015). Today, CLT in Europe competes successfully with steel, concrete, masonry, and light frame wood structures owing to the combination of lightness, intrinsic insulating properties, proven seismic performance, and ease and short-duration of construction, which can translate into low cost of construction (Laguarda Mallo and Espinoza 2015).

The development of CLT technology has been observed with growing interest in North America, so much so, that CLT handbooks have been published in Canada (2010) and in the US (2012) (FPInnovations and Council 2013), followed by ANSI/APA PRG 320-2012 performance standard in 2011, revised in 2012 and 2017. These developments have led to the adoption of CLT into the International Building Code (IBC) 2015 (Council 2015).

1.7 Development of CLT in North America

CLT is still relatively new to North America. Four companies are manufacturing CLT as of the end of 2016: Smartlam (Whitefish, MT, USA), D.R. Johnson (Riddle, OR, USA), StructurLam (Penticton, B.C., Canada), and Nordic Structures (Montreal, QC, Canada). CLT had a slow beginning, but interest has grown due to the perception of its competitiveness in construction with steel and concrete within the mid-rise building sector, and its high level of prefabrication (FPInnovations and Council 2013). An alternative use of CLT is in crane mats for use in the construction industry, but not classified as structural material in the U.S; CLT crane mates are produced by Smartlam and Sterling Co.

1.8 North American Product Standard (PRG 320-2012)

The need for a standard for qualification and quality control criteria for CLT panels intended for structural use led to the development of the PRG 320-2012 CLT product standard. The process began in 2010 when the APA Engineered Wood Products (APA) standards committee set out to develop an international standard for Cross Laminated Timber for North American market (Canada and USA). This standard is based on input from around the world (ANSI 2012). The most recent revision of the standard has been completed and approved in winter 2017. This study was guided by the preceding revision of the standard (PRG 320-2012).

The PRG320-2012 is a prescriptive product standard that dictates species, grades for lumber to be used in CLT laminations, and qualification criteria for bond integrity and finished panels. The standard clarifies the terminology, specifies panel dimensions and tolerances, component requirements (lumber and adhesives), performance requirements for standard CLT grades, qualification criteria for layups, qualification and quality assurance test procedures, as well as other manufacturing aspects.

To be qualified for structural uses, CLT must meet standard minimum bond integrity criteria specified by the North American product standard (ANSI/APA PRG320-2012), determined through laboratory testing for delamination (≤5%) and shear resistance (≥80% wood failure).

The bond integrity testing methods, or minimum qualification criteria (based on the resistance to shear and cyclic delamination test), were adapted from the American Institute of Timber Construction (AITC) glulam standard. PRG 320-2012 refers to existing external standards: ASTM D405 for preapproved resins, AITC T110 for delamination testing, and AITC T107 for block shear testing. The minimum qualifications that must be met by the panels are AITC T110 and T107 for the adhesive bond integrity in the panels.

1.8.1. Standard CLT Grades

The PRG 320-2012 specifies seven pre-qualified CLT grades that were thought to cover the large majority of materials to be used in construction. These seven grades consist of four CLT lumber grades defined for mechanically graded (MSR) laminations (E1, E2, E3 and E4) and three CLT lumber grades defined for visually graded laminations (V1, V2 and V3) graded groups that then correlate with a group of species (Service et al. 2010). Even with these predefined lumber grades, much of the CLT volume produced globally is custom fabricated and engineered for specific projects.

The values for characteristics and design values for prequalified PRG 320-2012 CLT grades are specified in Table 1 and Table A2 of the PRG 320-2012 standard (reproduction in Figure 3 and Figure 4).

TABLE 1

REQUIRED CHARACTERISTIC TEST VALUES[a,b,c,d] FOR PRG 320 CLT

CLT Grades	Major Strength Direction $f_{b,0}$ (psi)	E_0 (10^6 psi)	$f_{t,0}$ (psi)	$f_{c,0}$ (psi)	$f_{v,0}$ (psi)	$f_{s,0}$ (psi)	Minor Strength Direction $f_{b,90}$ (psi)	E_{90} (10^6 psi)	$f_{t,90}$ (psi)	$f_{c,90}$ (psi)	$f_{v,90}$ (psi)	$f_{s,90}$ (psi)
E1	4,095	1.7	2,885	3,420	425	140	1,050	1.2	525	1,235	425	140
E2	3,465	1.5	2,140	3,230	565	190	1,100	1.4	680	1,470	565	190
E3	2,520	1.2	1,260	2,660	345	115	735	0.9	315	900	345	115
E4	4,095	1.7	2,885	3,420	550	180	1,205	1.4	680	1,565	550	180
V1	1,890	1.6	1,205	2,565	565	190	1,100	1.4	680	1,470	565	190
V2	1,835	1.4	945	2,185	425	140	1,050	1.2	525	1,235	425	140
V3	2,045	1.6	1,155	2,755	550	180	1,205	1.4	680	1,565	550	180

For SI: 1 psi = 0.006895 MPa

(a) See Section 4 for symbols.

(b) Tabulated values are test values and shall not be used for design. See Annex A for design properties.

(c) Custom CLT grades that are not listed in this table shall be permitted in accordance with Section 7.2.1.

(d) The characteristic values shall be determined as follows from the published allowable design value unless otherwise justified by the approved agency:

f_b = 2.1 x published allowable bending stress (F_b),

f_t = 2.1 x published allowable tensile stress (F_t),

f_c = 1.9 x published allowable compressive stress parallel to grain (F_c),

f_v = 3.15 x published allowable shear stress (F_v), and

f_s = 1/3 x calculated f_v.

Note 7. The "E" designation indicates a CLT layup based on the use of E-rated or MSR laminations in the parallel layers, and the "V" designation indicates a CLT layup based on the use of visually graded laminations in the parallel layers. Visually graded laminations are used in the perpendicular layers for both "E" and "V" layups. The specific species and grade of the parallel layers and the corresponding perpendicular layers for each "E" and "V" designation are based on the following layups:

- *E1: 1950f-1.7E Spruce-pine-fir MSR lumber in all parallel layers and No. 3 Spruce-pine-fir lumber in all perpendicular layers*
- *E2: 1650f-1.5E Douglas fir-Larch MSR lumber in all parallel layers and No. 3 Douglas fir-Larch lumber in all perpendicular layers*
- *E3: 1200f-1.2E Eastern Softwoods, Northern Species, or Western Woods MSR lumber in all parallel layers and No. 3 Eastern Softwoods, Northern Species, or Western Woods lumber in all perpendicular layers*
- *E4: 1950f-1.7E Southern pine MSR lumber in all parallel layers and No. 3 Southern pine lumber in all perpendicular layers*
- *V1: No. 2 Douglas fir-Larch lumber in all parallel layers and No. 3 Douglas fir-Larch lumber in all perpendicular layers*
- *V2: No. 1/No. 2 Spruce-pine-fir lumber in all parallel layers and No. 3 Spruce-pine-fir lumber in all perpendicular layers*
- *V3: No. 2 Southern pine lumber in all parallel layers and No. 3 Southern pine lumber in all perpendicular layers*

Figure 3: Required Characteristic values for pre-defined CLT lumber grades set by the PRG 320-2012.(ANSI 2012)

TABLE A2.
THE ALLOWABLE BENDING CAPACITIES[a,b,c] FOR CLT LISTED IN TABLE A1 (FOR USE IN THE U.S.)

CLT Grade	CLT t (in.)	Lamination Thickness (in.) in CLT Layup							Major Strength Direction			Minor Strength Direction		
		=	⊥	=	⊥	=	⊥	=	$F_bS_{eff,0}$ (lbf-ft/ft)	$EI_{eff,0}$ (10^6 lbf-in.²/ft)	$GA_{eff,0}$ (10^6 lbf/ft)	$F_bS_{eff,90}$ (lbf-ft/ft)	$EI_{eff,90}$ (10^6 lbf-in.²/ft)	$GA_{eff,90}$ (10^6 lbf/ft)
E1	4 1/8	1 3/8	1 3/8	1 3/8					4,525	115	0.46	160	3.1	0.61
	6 7/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8			10,400	440	0.92	1,370	81	1.2
	9 5/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	18,375	1,089	1.4	3,125	309	1.8
E2	4 1/8	1 3/8	1 3/8	1 3/8					3,825	102	0.53	165	3.6	0.56
	6 7/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8			8,825	389	1.1	1,430	95	1.1
	9 5/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	15,600	963	1.6	3,275	360	1.7
E3	4 1/8	1 3/8	1 3/8	1 3/8					2,800	81	0.35	110	2.3	0.44
	6 7/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8			6,400	311	0.69	955	61	0.87
	9 5/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	11,325	769	1.0	2,180	232	1.3
E4	4 1/8	1 3/8	1 3/8	1 3/8					4,525	115	0.53	180	3.6	0.63
	6 7/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8			10,425	441	1.1	1,570	95	1.3
	9 5/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	18,400	1,090	1.6	3,575	360	1.9
V1	4 1/8	1 3/8	1 3/8	1 3/8					2,090	108	0.53	165	3.6	0.59
	6 7/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8			4,800	415	1.1	1,430	95	1.2
	9 5/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	8,500	1,027	1.6	3,275	360	1.8
V2	4 1/8	1 3/8	1 3/8	1 3/8					2,030	95	0.46	160	3.1	0.52
	6 7/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8			4,675	363	0.91	1,370	81	1.0
	9 5/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	8,275	898	1.4	3,125	309	1.6
V3	4 1/8	1 3/8	1 3/8	1 3/8					2,270	108	0.53	180	3.6	0.59
	6 7/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8			5,200	415	1.1	1,570	95	1.2
	9 5/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	1 3/8	9,200	1,027	1.6	3,575	360	1.8

For SI: 1 in. = 25.4 mm; 1 ft = 304.8 mm; 1 lbf = 4.448 N

(a) See Section 4 for symbols.

(b) This table represents one of many possibilities that the CLT could be manufactured by varying lamination grades, thicknesses, orientations, and layer arrangements in the layup.

(c) Custom CLT grades that are not listed in this table shall be permitted in accordance with Section 7.2.1.

Figure 4: Allowable bending characteristics set by the PRG 320-2012.

1.8.2 Custom CLT Layups

The published predefined grades are seen as a starting point and a company may define and certify a custom layup developed for a specific project. The PRG 320-2012 also allows for custom grades to be defined, tested and certified by the APA. The custom CLT grades are intended for layups that are different from the layups provided by Tables 1, A1, A2, A3, and A4, and may include double outer layers or unbalanced layups when clearly identified for installation, as required by the manufacturer and the approved agency (ANSI 2012).

All pre-qualified PRG 320-2012 grades also require a minimum of a No. 3 visual grade lumber in the minor direction of the panels and No.2 visual grade in all the major direction layers. SmartLam, a CLT manufacturer located in Montana, has already taken advantage of the ability to create their own custom CLT grade, called SL-V4 SPF-S (SmartLam 2017).

PRG320-2012 standard allows custom CLT grades to be composed of alternative grades and species, which theoretically makes it possible to use underutilized species in structural CLT panels.

Kramer et al. (2013), investigated using FSC certified plantation grown low-density species, such as hybrid poplar, for building structural grade CLT panels. The results showed that the material met shear and bending benchmarks for the predefined PRG 320-2012 E3 grade, but did not meet the stiffness benchmark (E) (Kramer et al. 2013). Southern Pine was investigated by Hindman and Bouldin (2015); the panels produced in the study did not meet the delamination tests, but “the bending strength, bending stiffness, and resistance to shear by compression loading properties met or exceeded the requirements of the V3 grade CLT defined in ANSI/APA PRG 320-2012” (Hindman and Bouldin 2015).

Another study conducted in Europe investigated European spruce (*Picea abies*) on the face layers and European beech (*Fagus sylvatica*) in the core layer of a 3-ply panel; concluded, that there is “extremely promising” potential of softwood-hardwood hybrid CLT layups (Aicher et al. 2016). Irish Sitka spruce, in a separate study, was used for homogeneous CLT panels and found that “for some of the specimens, minor manufacturing defects resulted in delamination failure rather than bending or shear failure… [emphasizing] the importance of proper quality production, especially the bonding process” (Sikora et al. 2016).

The CLT grade characteristics of interest for this project include: modulus of rupture ($f_{b,0}$), modulus of elasticity (E_0), and shear strength ($f_{v,0}$), where the major strength direction (subtext 0) refers to the general direction of the grain of the parallel layers and minor strength direction (subtext 90) refers to the direction perpendicular to the major strength direction of the panel (ANSI 2012) (Figure 1).

1.8.3 Lumber Grading

The pre-qualified grades set in the PRG 320-2012 are defined for standard lumber grades specified for the North American lumber market as listed in the footnote of PRG 320-2012 Table 1.

Visual grading is based on characteristics that can be visually seen, MSR grading allows for a better sorting of the material specific to an application and where the material is sent through a non-destructive machine for measurements of E (Kretschmann and Green 1999). These two grading types allow for lumber to be sorted into different stress grades for different applications.

Common characteristics that define lumber grades, include (WWPA 2011):

- Checks
- Grain (appearance & quality)
- Knots
- Manufacture
- Pitch and Pitch streaks
- Pitch or Bark Pockets
- Shake
- Skips
- Slope of grain
- Splits
- Stain
- Unsound Wood
- Wane
- Warp
- White speck

The WWPA specifies maximum defect characteristics (i.e. sizes and appearance) for a lumber grade (WWPA 2011). The customer can specify tighter tolerances for defects, such as wane.

Lumber can also be graded by a machine stress rating (MSR). Not all mills participate in this type of grading, which is typically geared towards lumber used in engineered wood products. MSR graded lumber is used in the PRG 320-2012 E grades.

The current product standard, PRG 320-2012, specifies that dimension lumber of No.2 grade is suitable for major direction of CLT panels and No.3 and better grade can be used in the minor direction. The characteristics for the No. 2 and No.3 structural light frame grades, as well as the Utility grade for light framing, outlined by the WWPA are listed below, in Table 1.

Table 1: Summarized WWPA characteristics outlined for the No.2 and No.3 Structural Light Framing grades (WWPA 2011).

Grading Characteristic	No. 2 Structural Light Frame	No. 3 Structural Light Frame	Utility Light Framing
Checks	Seasoning checks not limited. Through checks at ends are limited as splits.		
Grain	Medium.	N/A	
Knots	Well-spaced knots of any quality and are permitted in sizes not to exceed 2 in.	Well-spaced knots of any quality and are permitted in sizes not to exceed 2.5 in.	Not restricted as to quality and are permitted in sizes not to exceed 2.5 in.
Manufacture	Standard "F"		
Pitch and Pocket streaks	Not limited		
Pockets, Pitch, or Bark	Not limited		
Shake	If through at ends, limited as splits. Single shakes shall not exceed 3 ft. long or ¼ the length, whichever is greater.	Surface shakes permitted. If through at ends, limited as splits. Elsewhere, 1/3 the length, scattered along the length.	
Skips	Hit and miss, with a maximum of 5% of the pieces containing hit and miss	Hit and miss, with a maximum of 10% of the pieces containing heavy skips.	
Slope of Grain	1 in 8	1 in 4	
Splits	Equal in length to 1.5 times the width of the piece	Equal to 1/6 the length of the piece	
Stain	Stained sapwood. Firm heart stain or firm red heart. Not limited	Stained wood, not limited.	
Unsound Wood	Not permitted in thicknesses over 2 in.; in 2 in lumber, small spots or streaks of firm honeycomb or peck are limited to 1/6th the width.	Must not destroy the nailing edge. Spots or streaks limited to 1/3 the cross section at any point along the length.	
Wane	1/3 the thickness and 1/3 the width full length, or equivalent on each face, provided that wan not exceed 2/3 the thickness or ½ the width for up to ¼ the length.	1/2 the thickness and 1/2the width full length, or equivalent on each face, provided that wan not exceed 7/8 the thickness or 3/4 the width for up to 1/4 the length.	
Warp	Light.	Medium.	
White Speck	Firm, 1/3 the face or equivalent.	Firm.	

1.8.4 Adhesives

According to the PRG 320-2012 Section 6.3, all adhesives to be used for CLT in the U.S. must meet the requirements of AITC 405-2005. This standard is also the one used for Glulam. Adhesives currently covered by this standard are: melamine formaldehyde (MF), resorcinol formaldehyde (RF), phenol resorcinol formaldehyde (PRF), and melamine urea formaldehyde (MUF). However, about 80% of CLT manufactured globally is bonded with polyurethane resin (PUR), which is not listed within the AITC 405.

1.8.5 Thickness Tolerance

One of the most important differences between glulam and CLT is the requirement for tight thickness tolerances in cross-laminated layups. Even small variations in thicker laminations within the same layer may negatively affect the uniformity of pressure distribution between layers and impact the prospects for creating an adequate bond (Figure 6a and 6b).

The PRG 320-2012 specifies tight thickness tolerances for the lumber used within CLT panels. These tolerances are described in section 6.1.6 and should not exceed ±0.008 inches (0.2 mm) across the width and ±0.012 inches (0.3 mm) across the length of individual laminations.

It is important to note that many defects can be mitigated throughout the manufacturing process. Presence of substantial twist in laminations may negatively affect the thickness tolerances in layers, if pieces are not significantly pressed to the base during planing.

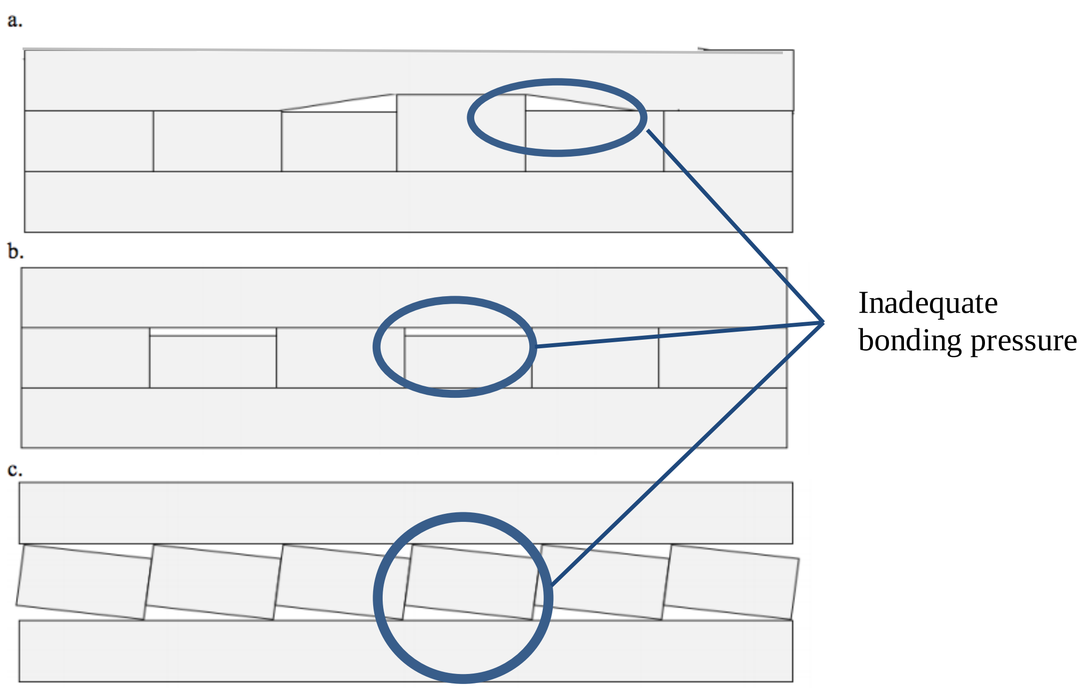


Figure 5: Illustrations showing potential layer gaps from laminations that are too thick (a.), too thin (b.), and twist (c.).(Larkin 2017)

Some of the possible scenarios can be seen in Figure 5. As long as the twisted pieces are properly planed the laminating can be flattened out in the press if sufficient pressure is applied. Similarly, with substantial pressure it is possible to close smaller gaps created by loosed thickness tolerances. However, the remaining bondline will have a residual stress after pressing and could result in unpredictable bondline failures (Larkin 2017).

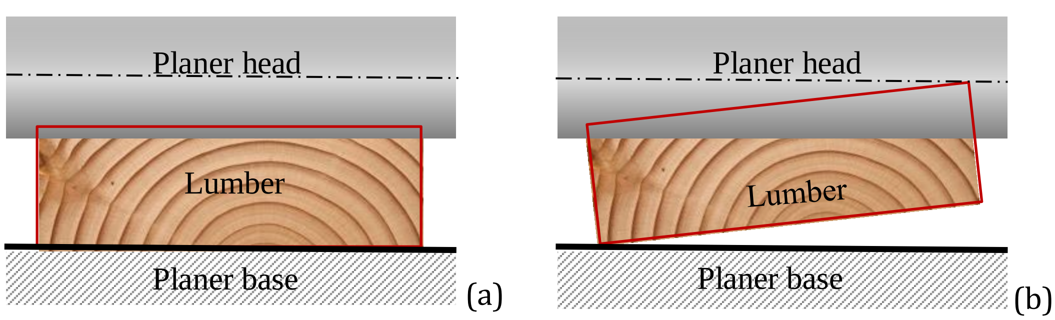


Figure 6: (a) A flat piece of lumber running through a planer, which is represented by the orange blocks. (b) A twisted piece of lumber that is being run through a planer changing the thickness.

Thickness tolerances may be substantially affected when severely twisted pieces are not sufficiently flattened during planning (Figure 5).

1.8.5 PRG 320-2012 prequalification procedures and criteria

The PRG 320-2012 Section 8.2 sets requirements for prequalifying new CLT products and product variations proposed by manufacturing companies. According to section 8.6: "material changes to the manufacturing process or facilities shall be subjected to subsequent qualification testing and the requirements of sections 8.2, 8.3, and 8.4 shall be reapplied for material changes listed or equivalent to that listed in Table 3 [of the PRG 320-2012]" (ANSI 2012). Table 3 of the PRG 320-2012 can be found in Figure 7 below.

TABLE 3
SUBSEQUENT QUALIFICATION IN RESPONSE TO MATERIAL CHANGES

Category	Applicable Sections	Material Change (examples)	Notes
A	8.2, 8.3, 8.4	• Press equipment • Adhesive formulation class • Addition or substitution of species from a different species group • Changes to the visual grading rules that reduce the effective bond area or the effectiveness of the applied pressure (e.g., warp permitted)	Excludes replacement with identical press
B	8.2, 8.3	• Other changes to the manufacturing process or component quality not listed above • Adhesive composition (e.g., fillers and extenders)	Additional evaluation in accordance with Section 8.4 is at the discretion of the approved agency[a]
C	8.4	• Increase in panel width or length of more than 20%	

(a) It is recommended that changes involving two or more manufacturing parameters be subjected to evaluation in accordance with Section 8.4.

Figure 7: Table 3 of the PRG 320-2012, which can be found in Section 8.6 Process Changes Qualification.

The critical PRG320-2012 criteria for the certification of a CLT product for structural uses are related to bond integrity: resistance to shear (examined in block shear tests) and delamination (examined after a rapid soak-dry cycle).

A minimum of six specimens must be tested for each new CLT product combination (by either of these two tests), three specimens per panel from at least two panels.

A shear resistance test (or block shear test) is done by applying pressure on one-half of a bondline until failure in order to examine the wood failure percentage versus adhesive failure to assess the shear resistance of the bond.

An average wood failure at or above 80% for all specimens of the new product must be met to qualify a product for certification for structural uses.

The cyclic delamination test is conducted by first pulling a vacuum (25 hg/in.), followed by a pressure cycle (at 75 psi) in a submerged state to force water into wood specimens and then rapidly dried in an oven at 160 ºF with forced air circulation for a minimum of 10 hours or until re-dried to within 15% of the original dry weight.

A 5% delamination or below on an individual specimen criterion needs to be met to qualify a CLT layup for structural uses per PRG 320-2012.

Samples for prequalification tests are pulled according to a specified cut-out pattern. Prequalification samples cannot be made within the same panel and the prototype panels must have a minimum size of 24 in. by 18 in. in the major and minor directions, respectively. However, it is recommended within the standards to use panels of no less than 24 inches in both directions as well (ANSI 2012). An example of the cut pattern recommended and the number of samples extracted can be seen in Figure 8.

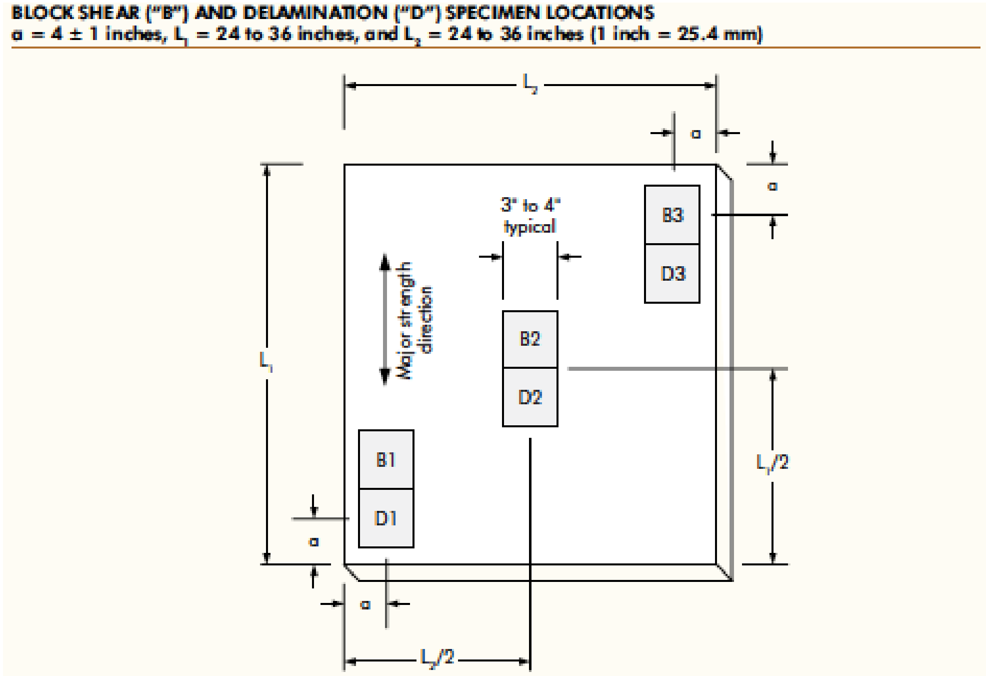


Figure 8: Required cutout pattern of prequalification samples from a produced panel. Figure 1, page 13 within the PRG 320-2012. (ANSI 2012)

1.9 Specific objectives of the project

Therefore, the specific objectives of the project were to:

(1) Determine if CLT panels utilizing low-value lumber from forest restoration operations in core layers of laminations meet PRG 320-2012 product qualification criteria;

(2) based on findings of Objective 1, propose respective changes to the current North American product standard PRG 320-2012 to allow low-grade forest restoration material in structural CLT products;

(3) Investigate the impact of small logs from forest restoration programs on the efficiency of the primary and secondary processing; and

(4) Assess the effects of regional logistics options (location of the primary processing, transportation routes/costs) on the commercial viability of the utilization scheme.

This thesis is concerned with the technical viability portion of this project and focused on objectives 1, 2, and partly 3. Certain aspects of objective 3 and objective 4 are addressed in a parallel study (Lawrence 2017).

Successful demonstration of this project is expected to provide a new and innovative outlet for the small logs generated in forest restoration options in value-added products that could be added to the existing channels, increasing the diversity and improving the stability of the market, and supporting the expansion of pace and scale of the forestland restoration projects. It would also inform future investments and resource utilization and would have the potential to lay the foundation for future markets in areas dependent on forest products.

CHAPTER 2: MATERIALS AND METHODS

The project was performed in two major steps related to Objectives 1 and 3. The approach related to objective 3 was to select industrial representatives of the potential supply chain for the forest restoration material in the Pacific Northwest region, follow a sample of small logs harvested in a selected restoration area through processing stages, and to assess the impact of the material on the primary processing and CLT lamination. Being able to follow the entire process of production for this project allowed for challenges in current industry practices to come to light when harvesting and processing this material. These were important observations due to the unique characteristics of the material, which is not commonly used within the lumber and CLT industry.

The approach related to Objective 1 was to perform qualification tests on the 3- and 5-layer CLT layups incorporating the forest restoration material in core layers. Bond integrity qualification tests and bending tests aimed at determination of basic engineering characteristics were conducted per ANSI/APA PRG 320-2012 standard. Bending characteristics were compared with the benchmarks for PRG 320-2012 prequalified CLT grade E3.

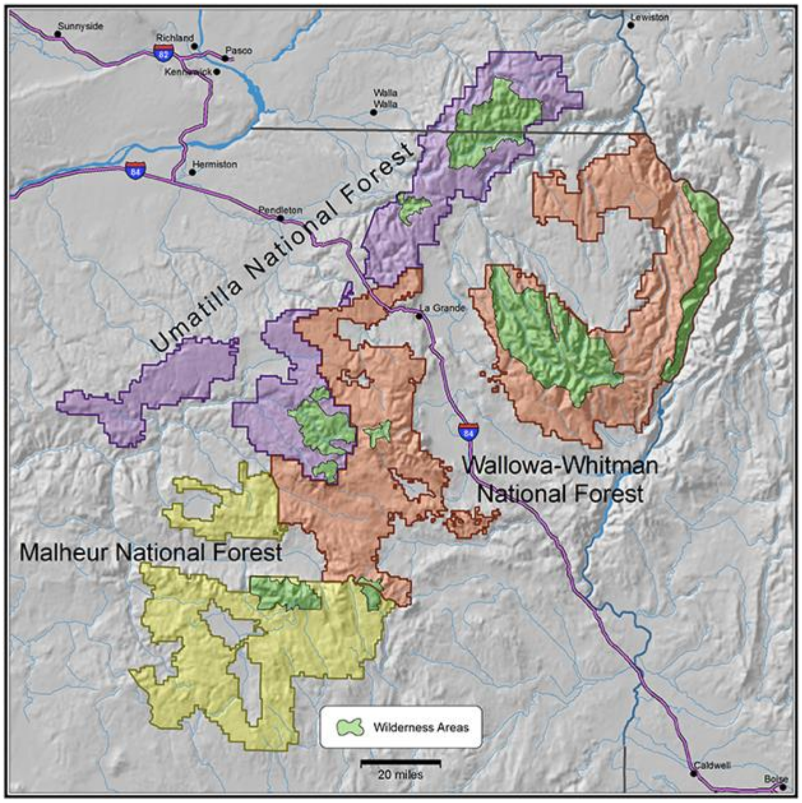


Figure 9: Area and forests that are included in the Blue Mountain range. (BMAP, n.d.)

2.1 Raw material source

Figure 10 outlines the path of the material specific to the project. Logs were generated in forest restoration thinnings from the Malheur forest (1) were then transported to Lewiston, ID (2) for breakdown. Collins Lumber Company (4) breaks down timber generated in USFS forest restoration. Lumber from both sources was then transported to D.R. Johnson (3) for panel production and tested at Oregon State University (5).

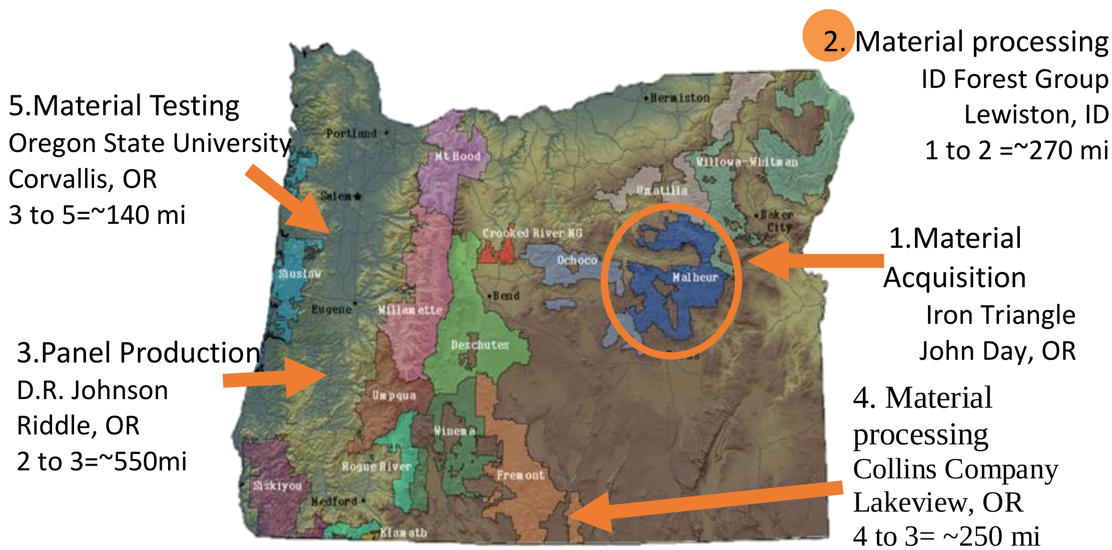


Figure 10: Map and locations of where harvesting, lumber production, panel production, and testing occurred.

2.1.1 Iron Triangle

Most of the material used for this project was generated in the Malheur National Forest administered by the United States Department of Agriculture Forest Service (USFS) for National Forest System restoration programs.

2.1.1.1 Profile of the company

Iron Triangle LLC is the largest logging company in John Day, OR, with over 100 employees. The company won a 10-year stewardship contract for the Malheur National Forest in 2013 (Hammett 2013). This stewardship allowed the company to participate in restoration work that includes the removal of logs and biomass from large landscape areas in the Malheur National Forest (Hammett 2013).

2.1.1.2 Characterization of the restoration treatment

The Malheur forest (part of the Blue Mountain range) is located near John Day, OR (Figure 10) and is a cold, dry area. The Blue Mountains (Figure 9) have changed drastically over the last 150 years, since commercial harvesting started within the region (Rainville et al. 2008a). While the region was initially dominated by Ponderosa pine, minor fires and insect outbreaks caused the forest to change and become more diverse as time passed(Rainville et al. 2008a).

2.1.1.3 Thinning process

One of the goals of the project was to obtain material that is typically generated in thinnings. This was done to help determine if the small-diameter timber from the restoration practices would be acceptable for the lumber industry and CLT laminators. As stated above, many sawmills do not process logs below 6 inches on the small end.

The standard order of operation for thinning begins with selection of trees to be felled, falling these trees, de-limbing and finally transporting to a processing site.

The thinning operation is typically performed in the following steps:

1. Timber Selection (selective harvesting of stewardship)
2. Felling timber
3. Skidding (moving) of log to landing
4. On-site processing. This includes bucking (or cut to length, which is not always done) and de-limbing.
5. Transportation

The trees removed from the Malheur National Forest by Iron Triangle, LLC, is timber that is usually chipped and transported to downstream manufacturing. The thinning site was slightly sloped and, at the time of the visit, had snow present (Figure 11).

The thinning process performed by Iron Triangle, LLC was not much different from a standard thinning, except that the material was not chipped. This means that trees deemed good quality were left to grow further while trees deemed lower quality were removed.

Logs removed by Iron Triangle, LLC for this project were bucked to less than or equal to 12 feet.

Much of the timber removed was Ponderosa pine (*Pinus ponderosa*), followed by smaller amounts of White fir (*Abies concolor*) and Douglas-fir (*Pseudotsuga menziesii*).

Figure 11: Harvest site at Malheur National Forest near John Day, OR.

2.1.1.4 Log selection for the project

Iron Triangle sent three full truck loads to Idaho Forest Group's (IFG) mill located in Lewiston, ID (~268 mi). Specification for the project asked for a species mix characteristic for the restoration site and material with a 3.5 to 6-inch diameter on the small end of the log. However, due to a miscommunication the material sent for processing was not screened or pre-sorted, and included much thinner logs obviously not fit for lumber production (Figure 16, Figure 17, Figure 15). This contributed to the difficulties experienced during the lumber production at Idaho Forest Group's Lewiston, ID mill.

2.1.2 Collins Co.

While not originally planned, the Collins Company also donated material to the project at its later stage. Collins Co. has a stewardship contract with the USFS

Forest Service, they were an ideal company to work with and easily acquire additional material for this project.

2.1.2.1 Profile of the company

Collins Co. is a fifth-generation lumber company that has been operating for over 160 years. The company owns five mills that produce a range of products such as softwood and hardwood lumber, particleboard, and siding and trims. The company pursues stewardship contracts similar to Iron Triangle, LLC in John Day, OR. The Collins Co. Lakeview Sawmill located in Lakeview, OR works with timber sourced from 97,600 acres of southern Oregon and northeast California forest lands. These forests have a similar climate to the one found in the Blue Mountain forest region. The log size is similar as well, but diameters of logs processed in the Lakeview, OR mil range from 5 to 14 inches on the small end. Collins Co.'s stewardship contract, and associated regulations, allow the company to perform the thinning operations in the Fremont-Winema National Forest.

2.1.2.2 Characterization of the thinning site

As the material was donated and was part of the company's regular production of lumber from their restoration operations, a specific thinning site within the Fremont-Winema NF could not be immediately identified.

2.1.2.3 Harvesting process

Much of the material that is thinned by Collins is less than 12 inches in diameter with an average of 9.5 inches (Collins Co. 2017).

2.1.2.4 Log selection

The Lakeview, OR facility provides roughly 8 million feet of processed material from their own lands, an additional 15 million board feet comes off of federal forest land thinning operations, with any additional timber coming off of private lands. Much of the timber from the private lands is located in northern California and the Green Diamond area. Much of the material removed from federal forest land is chipped (~43%). The material produced into lumber is mainly turned into a 2x4 or 2x6. These 2x4s and 2x6s result in the following grades: 50% No. 2 and better, 30% Utility or No. 3, and the last 20% is other miscellaneous grades. Overall, the mill produces roughly 72 million board feet every year.

2.2 Log processing

Logs sent from the Malheur National Forest restoration site were processed at the Idaho Forest Group's Lewiston mill, as the company volunteered to breakdown the thinned material. Logs with rot, large sweep, diameters smaller than 3.5 inches on the small end, and other defects that prevented the breakdown by a HewSaw SL250(the main portion of the company's breakdown line) were causes to be removed and chipped. Logs harvested by Collins Co. were processed at their own small-log mill in Lakeview, OR.

2.2.1 Idaho Forest Group sawmill in Lewiston, ID

The Idaho Forest Group (IFG) sawmill in Lewiston, ID was updated within the last five years with the specific objective of extending the company's capacity for processing small logs (down to 3.5" on the small end). The centerpiece of the mill is a modern HewSaw SL250 line.

Once a mill receives logs, they begin the merchandising process. This process consists of scanning for any internal defects, cutting logs to length, checking the logs for any metal contaminants, and sorting into pre-set groups by IFG for maximum breakdown efficiency.

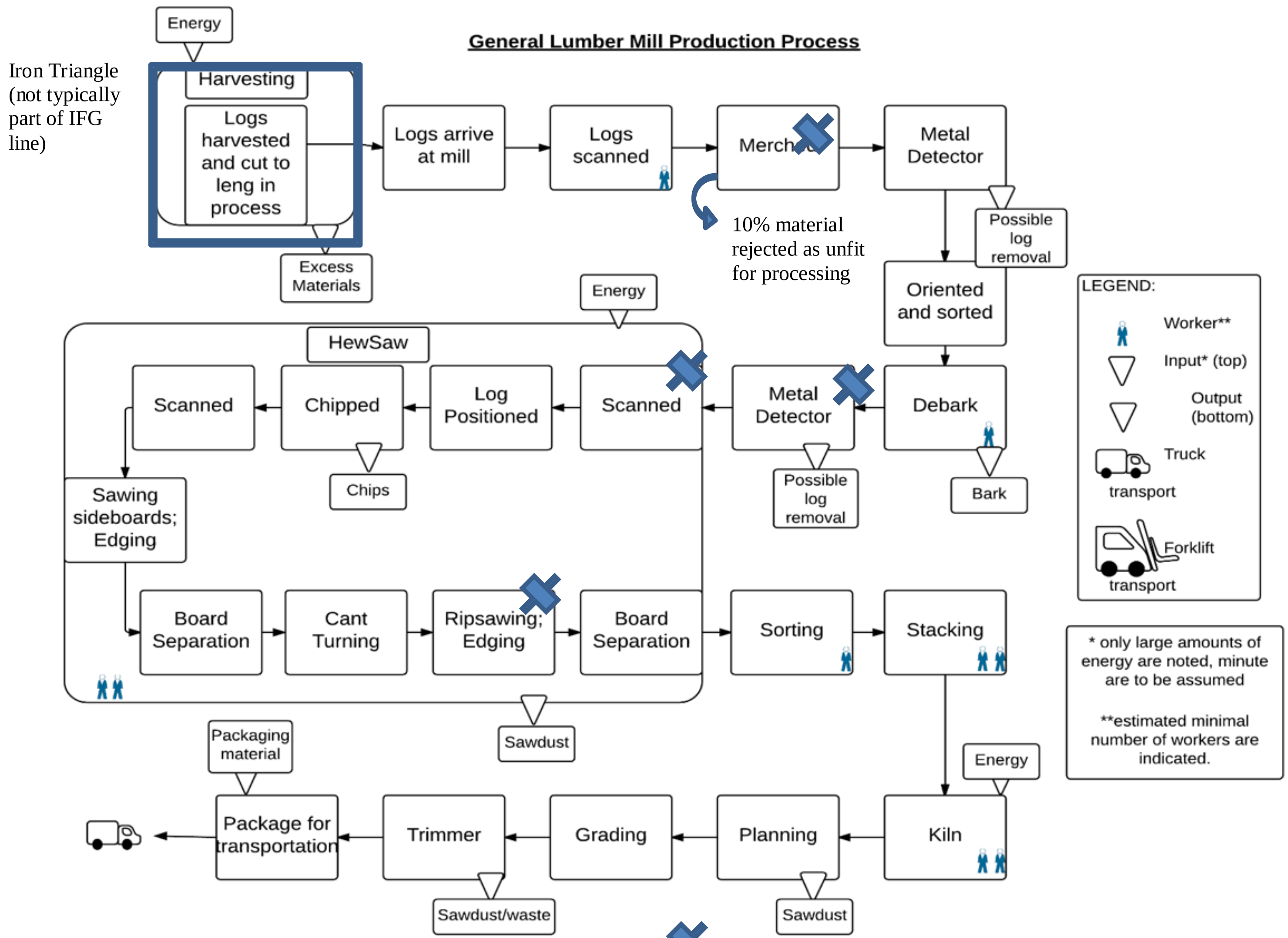


Figure 12: Idaho Forest Group's Lewiston, ID mill production flow-chart. [X symbol] *Indicates a problem at that step of production. Merched (merchandizing): many logs were not suitable to send through the merchandizing process because of rot, small diameter, etc. Scanned: additional logs were removed due to rot and other defects, unable to be processed. Ripsaw: Edging: while making it through most of the process, pieces broke during this section of production.*

2.2.1.1 The HewSaw line

The company was targeted for this project because the mill was recently up graded to using a HewSaw SL250. This is essentially a combination of multiple HewSaw machines strung together to completely breakdown logs. The SL250 breaks down the logs after the merchandising process. This means that once the log is scanned for defects and cut to length, it is sent through the HewSaw and then the timber is graded, stacked and prepared for drying. The diagram represents the breakdown process and can be found in Figure 12 and Figure 13.

The specifications for the HewSaw state that the line can cut anywhere from 3 inch to 16 ½ inch diameter logs on the top end. It was indicated during a site tour and interviews the company had no prior experience with material smaller than diameter of 4 ½ inches at the small end. This lack of experience made processing of some of logs less than 3 ½ inches on the small end substantially more difficult. However, the mill took the challenge as an opportunity to test the capabilities of their new process line, as they were still in the testing and training phase with the HewSaw. The trial was performed in the presence of a HewSaw representative from Finland.

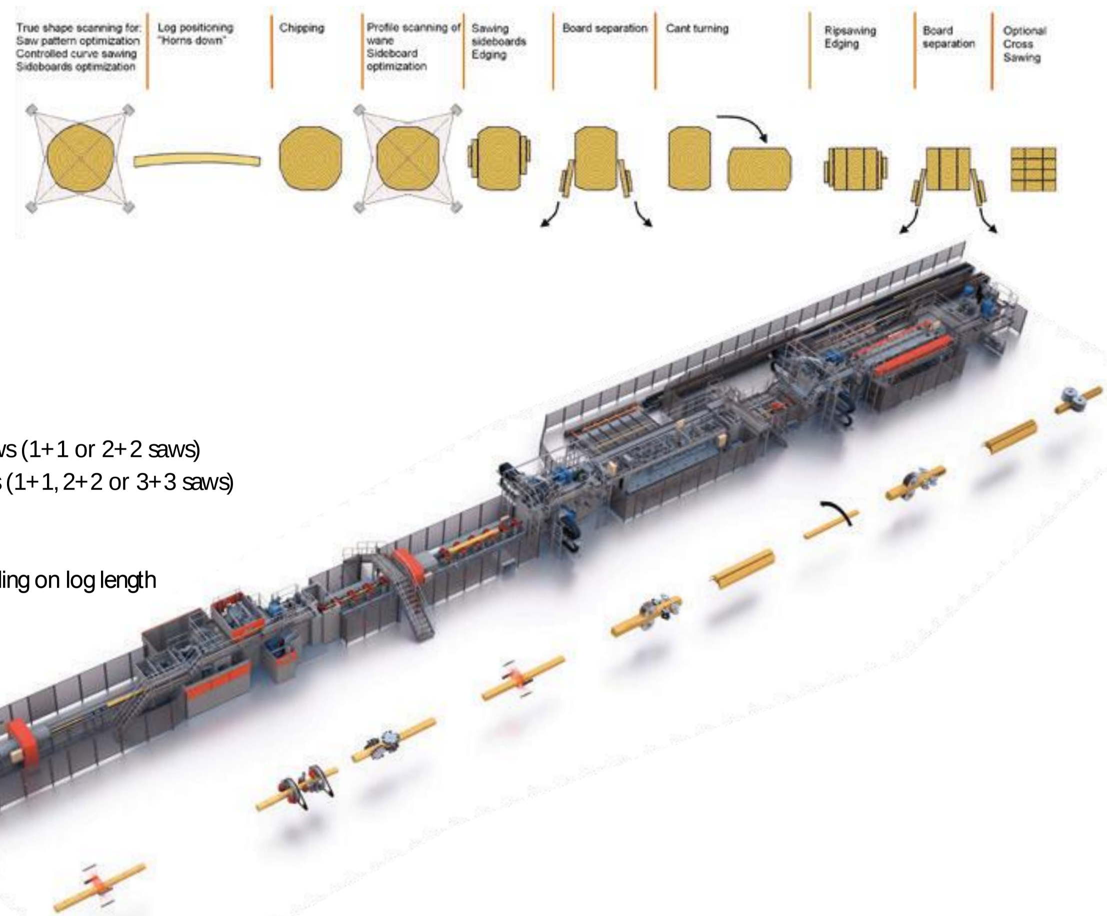
HewSaw Machines Inc.

HewSaw SL250 3.3/3.4

Precision sawing line with modern features

TECHNICAL DETAILS

Log diameter, top end	3˝ - 16 1/2˝
Maximum log diameter	21 1/2˝
Log length	8´ - 20´
Cant height in cant saw	3˝ - 15 3/8˝
Cant width in cant saw	3˝ - 15 3/8˝
Cant height in rip saw	2 1/2˝ - 10 1/2˝
Cant width in rip saw	3˝ - 15 3/8˝
Line speed	200 - 650 fpm
Chip length	3/4˝ - 1 1/4˝
Sawing options	Fixed saws Movable saws ▪ Cant saw: 2 - 4 saws (1+1 or 2+2 saws) ▪ Rip saw: 2 - 6 saws (1+1, 2+2 or 3+3 saws) ▪ Cross saw (CRS) ▪ Saw Guide System
Line length	230´ - 270´ (depending on log length and configuration)



HewSaw® HewSaw Machines Inc. | 2104 Townline Road | Abbotsford, BC V2T 6E6 Canada | Tel. 604 852 7293 | www.hewsaw.com | info@hewsaw.com

Figure 13:HewSaw process diagram. Includes breakdown process and technical details. (2User 2017)

2.2.1.2 Issues observed while processing the small logs from Iron Triangle

Because Iron Triangle sent logs without pre-sorting at the processing site and sent what is considered a pulp log sort, 10% of logs were rejected at the IFG log yard before the merchandizing process. This is not typical practice within the industry because of the high cost of log transportation.

The merching process revealed a large amount of material that could not be processed (10%). Some logs had undetected rotten cores or too much sweep (Figure 15) to be processed by the HewSaw; the defects were detected when scanned by the HewSaw for lumber recovery optimization. Some of these defects can be seen in Figure 15, Figure 16, and Figure 17.

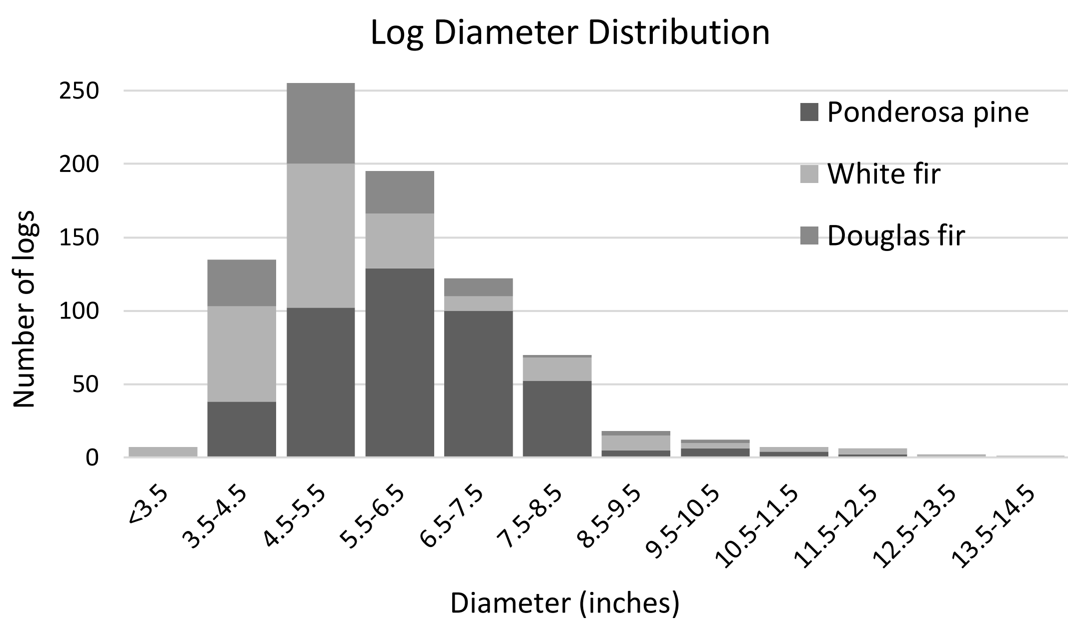


Figure 14: Summary of log diameters delivered to Idaho Forest Group by Iron Triangle.

The company’s HewSaw is set up to cut a minimum of a 3.5-inch, on the small end, diameter log and derive a minimum lumber size of 3” x 3” piece; most of the project’s logs of which were between 4.5 and 6.5 inches (Figure 14).

Below is a list of issues encountered while the project material was processed:

1. Additional time at merchandizing (material that should have been left at the thinning site to rot; seen in Figure 16, Figure 17, and Figure 15)
2. Repeated jams at the point where the transverse kicker was supposed to kick logs out of the belt sideways towards a transvers conveyor. These required personnel with a hook and/or chainsaw to unclog (substantial stoppage, Figure 18).
3. Log had no cut solution, so log was removed.
4. The log was bucked (cut) to short, causing the log to be removed.
5. Several pieces jammed in the HewSaw gang saw section (Figure 19).
6. And, at least in one case, a sawn piece still traveling together, past the first gang saw unit, got jammed on the conveyor (Figure 20).

The total amount of downtime observed during the shift in which the test material was processed added to 127 minutes, which is about a quarter of the shift and amounts to an estimated nearly $45,000 worth of estimated downtime (Lawrence 2017). Some of this downtime can be attributed to the facility not working with the small timber sizes before.

Figure 15: A delivered log to IFG that was rejected due to having too much sweep, or curvature to the log.

Figure 16:Rejected log at IFG during the merching process that contains rotted out core, bug defects, and exposed sap wood.

Figure 17: A log that was delivered, but is unable to be processed at IFG due to is very small diameter. An idea of the diameter can be seen by the business card held up, which is 3.5 inches in length.

Figure 18: Difficulties during the breakdown process. During the processing the material was rotated, causing it to get caught in the machinery and needing it to be removed. This occurred multiple times.

Figure 19: The HewSaw breakdown process began and was unable to continue through the saw, as the piece got jammed on the conveyor.

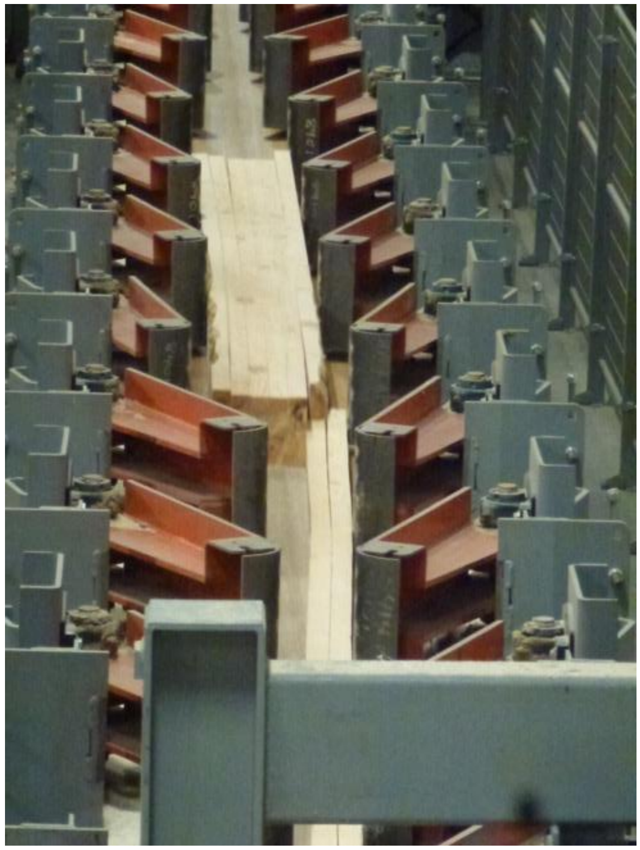


Figure 20: A sawn pieces still traveling together, past the first gang saw unit, got jammed on the conveyor.

2.2.1.3 Characterization of the processed lumber

Overall, based on the IFG shift summary provided by the Lewiston, ID mill, 16,167 boardfeet (bf) were produced from the thinned material (compared to an average of 65,000 bf per hour); this was a combination of Ponderosa pine (8,487 bf), White fir (5,482.7 bf), and Douglas-fir (2,197.3 bf). Much of the lumber that was produced consisted of 2x4 lumber (Figure 21) in lengths of 12-14 feet (Figure 22). Since much of the timber produced 2x4 lumber, this was deemed the dimension to use within the panels and to further breakdown larger dimensions for consistency. The 1x4 and 2x3 material was not used to keep consistency of the dimensions within the panels, but could be used in CLT panels overall. The other dimensions were used or broken down further, in to a 2x4, to be used within the panels.

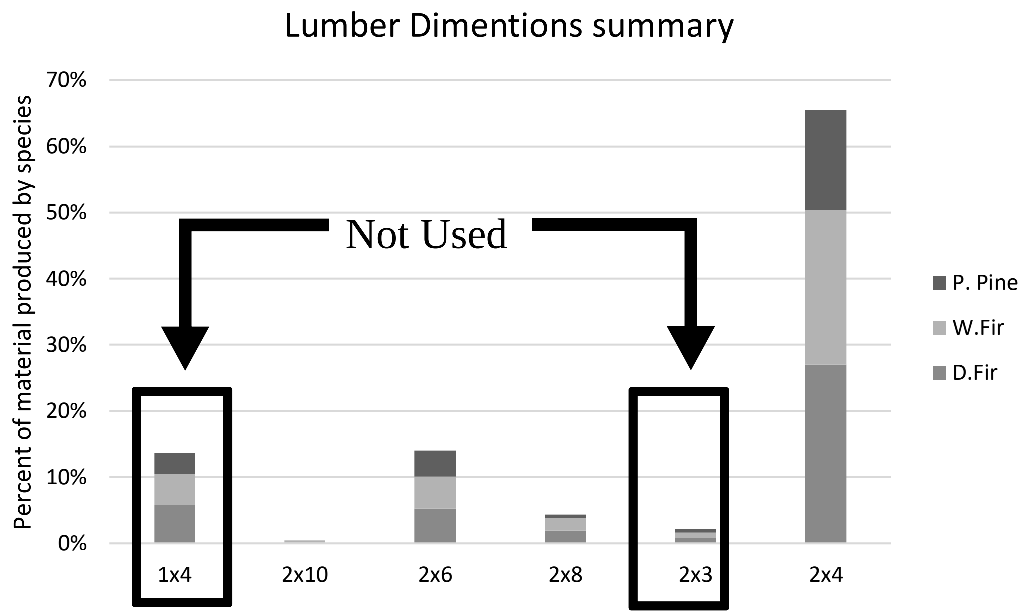


Figure 21: Summary of number of dimensions of lumber produced by material processed by Idaho Forest Group.

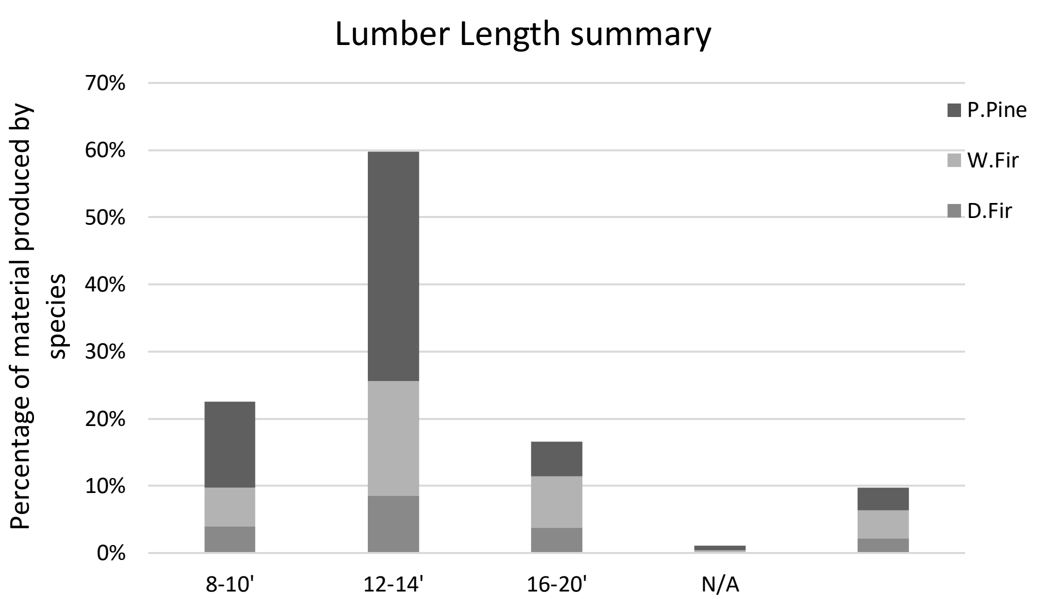


Figure 22: Summary of lengths of lumber produced by material processed by Idaho Forest Group.

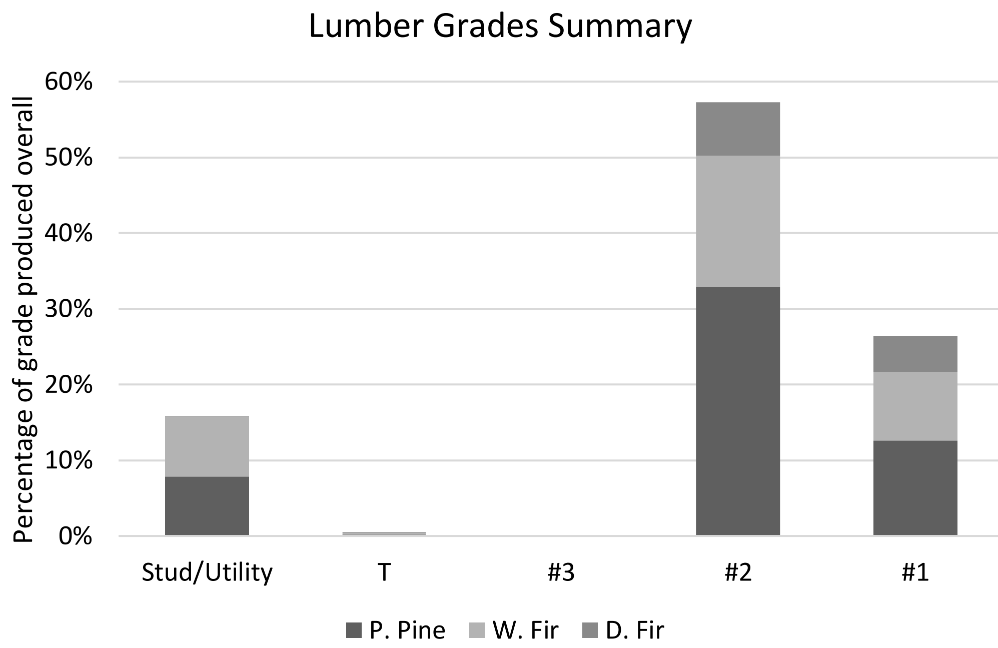


Figure 23: Summary of grades produced by lumber that was processed and graded at Idaho Forest Group Lewiston, ID mill and Collins Co. The mill produces a Home Center (HC) grade, which is a No.2 with a lower wane tolerance, so for this project the HC grade was treated as a No.2 and better grade.

The material harvested from the Malheur National forest mainly resulted in a No.1 and No. 2 Structural light frame visual grade.

Figure 24: An example of the amount of wane that was present throughout the processed material; this was compatible with the No.2 visual grade.

2.2.1.4 Drying

The lumber processed at IFG was then kiln dried to 12 ±3 % MC and transported to D.R. Johnson in Riddle, OR (~542 mi.) for the CLT panel production.

2.2.2 Collins Co.

After screening and removing the ~20% of logs provided by Iron Triangle, it was necessary to secure additional material for the test CLT panels. We used this opportunity to include Collins Co. as an alternative to Iron Triangle's forest stewardship contract and to Idaho Forest Group's small logs processing sawmill in the region of interest.

2.2.2.1 Description of Collins saw mill line

The timber thinned by Collins Co. consists of Ponderosa pine, White fir, Lodgepole pine and Incense cedar (*Calocedrus decurrens*). The Lakeview mill has a capacity of 65 million boardfeet a year, where its sawmill, planer, and dry kilns produce lumber anywhere from a 1x4 to 2x12 size and 8-16 feet in length (Lakeview Sawmill). Their facility practices processing small diameter logs between 5 to 14 inch diameters on the small end by using a USNR 2500 saw line; however, the saw can go down to a 3.5in. diameter log on the small end.

2.2.2.2 Issues with processing small diameter material

Collins Co. does not push its line to process logs smaller than 5 inches at the small end (but could go down to a 3.5 in.). We were unable to take a tour of the line and no problems were reported to us for processing the timber.

2.2.2.3 Characteristics of the processed lumber

The material from Collins Co. was already graded at their facility as a Utility grade. Which differs from No.3 visual grade lumber only in that it allows the knots to be clustered in the laminations (as opposed to “well spaced” in the No.2 visual grade. Characteristics of the grades can be found in Table 1).

2.2.2.4 Drying

The Collin Co. lumber is typically kiln dried to roughly 15%, which means that nearly half of the delivered lumber might have been above the 12+/- 3% tolerance required by the PRG 320-2012. While it is reasonable to assume that the pieces continued to dry at D.R. Johnson storage, awaiting the processing, the actual moisture content at the time of lamination has not been measured.

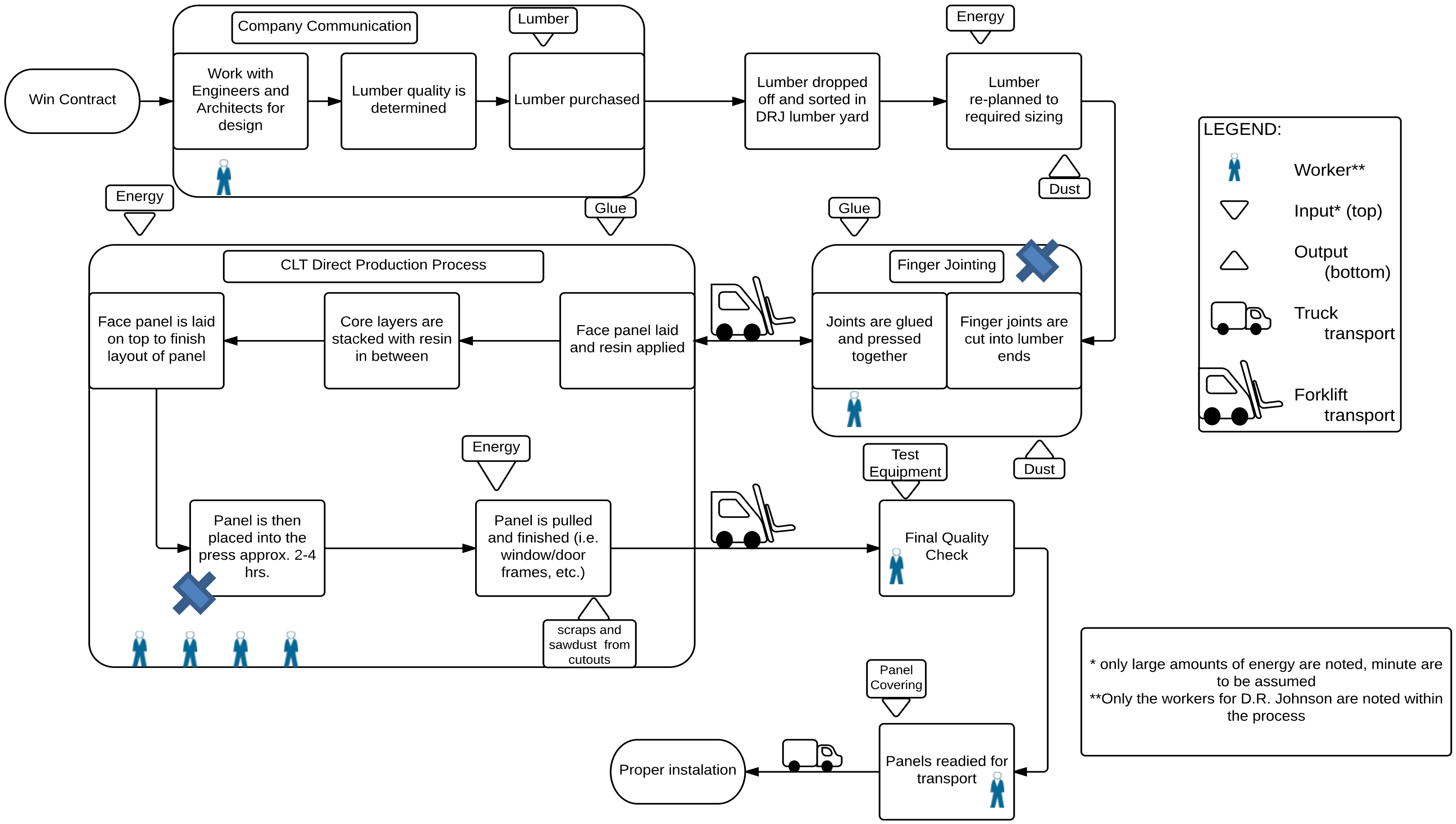


Figure 25:D.R.Johnson production flow-chart. Indicates a problem at that step of production. Finger jointing: pieces were removed due to rot. Press: more than normal warping, where additional effort needed to be made (Figure 31).

2.3 Processing CLT panels

Lumber mills are part of a custom-built industry, which causes no two lumber mills to be the same. These differences can be due to the area where a mill is located, machinery breakdowns and repairs, the availability of new and used machinery to address equipment breakdown in a timely manner, the maintenance budget of a mill, and the demand for the product the mill is producing, to name of few reasons. While each mill maintains an open-door policy, each also has a "secret sauce", or what they consider to be a secret twist, which makes them competitive against the other lumber mills. The up and coming CLT production is similar in this respect. Each of the companies that were visited for the project (Nordic Structures, Structurlam, Smartlam, and D.R. Johnson) are different in the setup of their production lines and each has their own way to gain a competitive advantage. More detailed information about the other manufacturers can be found in the trip reports located in APPENDIX A: Trip Reports.

2.3.1 Description of D.R. Johnson CLT line

D.R. Johnson was the first certified structural CLT manufacturer approved by the APA in the U.S.. The company built the panels for this project. The production line at D.R. Johnson is less automated than other manufacturers within North America, as the others have a much more continuous production lines. For instance at Structurlam, material is moved through the manufacturing facility by conveyors and vacuum lifts are used to layup panels.

D.R. Johnson replaned the material down to 1-5/16th inches before forming and gluing the finger joints (melamine from Moventive used). Essentially, during the finger-jointing process a continuous line of lumber was formed and then re-planed and cut down into the laminations designated for minor (width) and major (length) directions required of the CLT panel. The planing was done within the finger jointing step of production, where the wide face of the lumber is planed and then the sides are planed directly after the piece has been finger jointed. The major and minor directions of the panel are kept separately for an easier and quicker layup of the panels since it is done by hand. Currently, D.R. Johnson has gradually developed ways to use mechanical assistance for the minor direction of the layup process (Figure 33); however, this was not in place when they pressed the material harvested by Iron Triangle. The fork lift was used to layup laminations in the major direction, which can be seen in Figure 26. By the time the Collins Co. lumber was delivered, D.R. Johnson had added mechanical assistance for the minor direction layup process (Figure 33). Assistance, such as that seen in Figure 26, was not possible with the minor direction due to its short lengths. This setup for the minor direction reduced the amount of handling during the layup process; however, narrower 2x4 lumber still could not always be moved smoothly over the rollers and required adjustments. As a result, this additional setup did not seem to improve the efficiency of production of the test panels.

A business challenge that is present in the CLT industry, in particular for North America, is the unknown scale of which the CLT industry will become and what companies should do in order to expand production to match demand more easily. D.R. Johnson addressed this issue by having a modular press so it can be expanded lengthwise by adding frame modules, which allows the company to increase production in a cost effective and timely manner, along with the changing market. To complete the formation of the panels, the company uses a pneumatic press, designed by USNR, but fabricated mainly at their own fabrication shop.

Throughout the duration of this project the company expanded their press twice; this allowed them to go from 24 to 38 foot panels with ease.

The glue used for the panels was a two-part melamine formaldehyde (MF) manufactured by AkzoNobel, with spread rates between 73-100 lbs/Mft^2 (Table 2). This glue is sensitive to environmental and lumber temperatures, performing optimally between 70-75°F for the lumber (Lawrence and Brock 2017, Casco Adhesives 2009). The hardener and resin are kept separately (Figure 27) and are applied individually as parallel beads on the panels lay-up, combining only when the panel is pressed and the two parts spread and merge together. Ensuring that the resin is cured according to manufacturer's specs, each panel is pressed for an average of two hours with a 105 psi (Table 2). The press time and the ratio between the resin and the harder is adjusted if the environment or lumber is different than the optimal 70-75 °F range. The CLT panels with Iron Triangle, LLC material were produced within the week of June 1, 2016. The panels produced from Collins Co. lumber were pressed between January 18-20, 2017.

The company designs layups with an overhang on the edges of the panels to allow the in-plane pressure and ensure a tight layup and press of the panels (Figure 29).

The layup for each panel took 20-45 minutes and with lumber temperature ranging from 63-88°F (Table 2). Specific details of the panels production can be seen in Table 2. Since the project panels were smaller than the company's press, which was designed for (at the time) 10'x24' panels, side blocks and boards were used to fill the space and transfer the in-plane pressure (Figure 30).

After the panels were removed from the press they were moved to the Hundegger PBA Computer Numerical Control (CNC) machine to make the specified cuts. Panels from the press are moved to the CNC by a crane (Figure 32). Once the panel is placed on the stands for the CNC, the cut pattern is uploaded. The corner from which the cut pattern will be based is then selected to ensure a square cut. Before the Hundegger PBA, D.R. Johnson's CNC machine, was installed the company was using hand tools, such as skill saws and panels saws, for finishing cutouts to panels.

Figure 26: Layup of the major strength direction of the panels. One ply of lumber is laid-up on the forks of the forklift, which have wheels to roll the lumber off. The linemen simply need to ensure that the lumber is laid-up tightly.

Figure 27: Panel glue spread setup. The glue head moves along the minor direction of the panels lay-up, while the table, on which the panels is laid-up, moves in the major direction. The hardener and MF glue are kept separately and roll together when placed under pressure in the press.

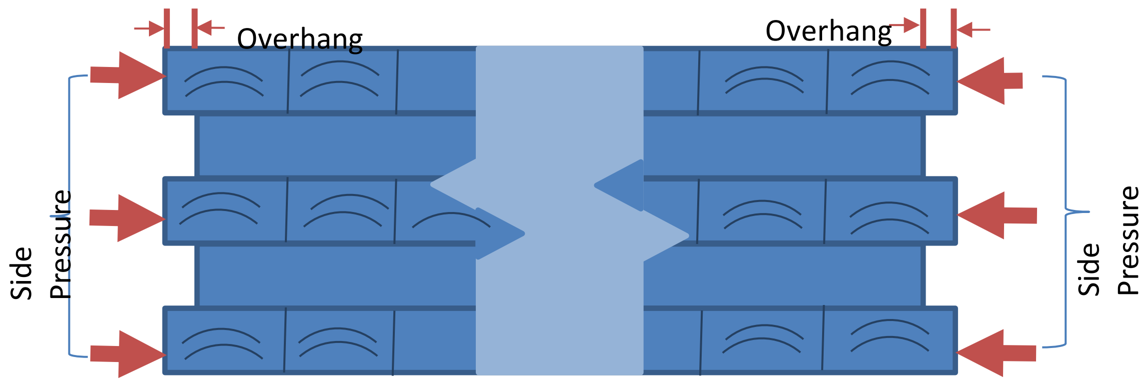


Figure 28: The design used by D.R. Johnson for overhang, this is used to ensure a tight layup of the panel once removed from the press.

Figure 29: Example of the overhang designed to ensure a tight layup.

Figure 30: The "filler" material that was used to accommodate the project's panel sizes that were smaller than the press was designed for. The red lines indicating the area that needed to be filled to accommodate the smaller panels sizes and transfer the in-plane pressure.

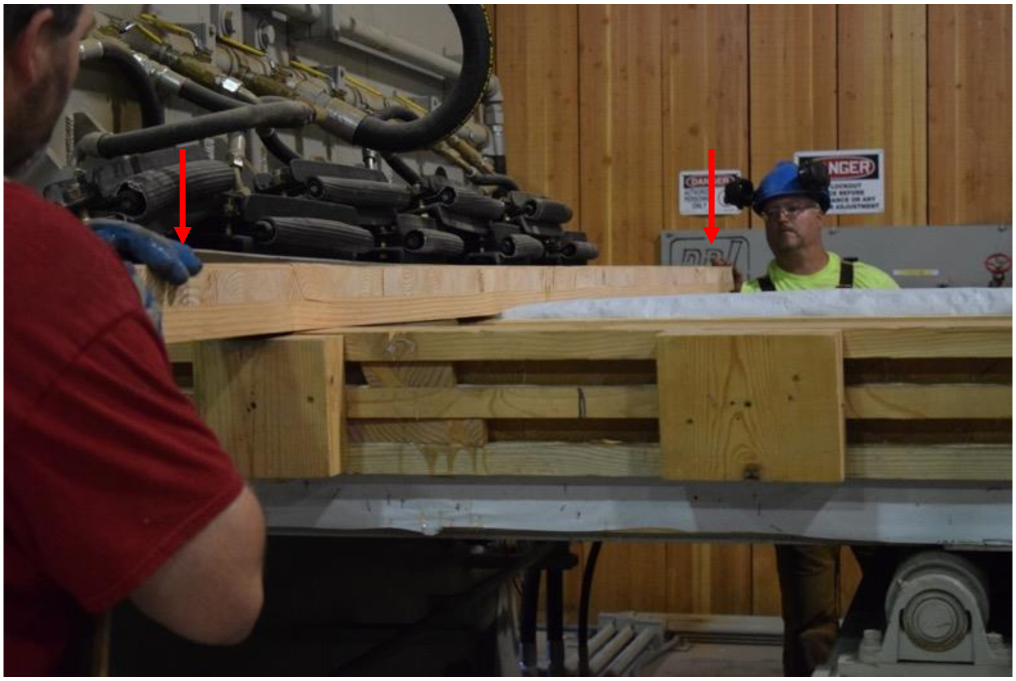


Figure 31: Because of warping, the panels had to be manually pressed down when loaded into the pneumatic press. The arrows indicating the pressure points on the board helping to squeeze the laid-up panel in the press.

Figure 32: The labor-intensive method used by D.R. Johnson to move the produced panel from the press to their CNC. The panel must be rotated, screws inserted, and the chains adjusted for stability.

Figure 33: The additional machine that D.R. Johnson used for assistance in the minor direction. This allowed for the lumber to be rolled on top of the previous layer as the staging area for the panel moved back and forth for a quicker and easier layup to help reduce open times.

Table 2: Details of production for each panel produced with thinned material at D.R. Johnson (Lawrence & Brock 2017). Original documents in Appendix B. Details of production for the panels produced with material from Collins Co. was unable to be obtained. These panels were processed in June.

Pane WF= White fir PP=Ponderosa pine DF=Douglas fir HS=Homogeneous Species	**WF & PP** HS **(3-ply)** **2 Panels**	**PP** HS **(5-ply)**	**WF** HS **(5-ply)**	**DF** HS **(3-ply)**	**DF** HS **(5-ply)**	**Mix** **(3-ply)** **2 panels**	**Mix** **(3-ply)**	**Mix** **(5-ply)**	**Mix** **(5-ply)**	**Mix** **(5-ply)**
Moisture Content	9-12%	9-12%	9-12%	9-13%	9-13%	9-13%	9-13%	9-13%	9-13%	9-13%
Air Temp (°F)	80	61	80	61	73	70	70	87	66	70
Lumber Temp (°F)	77	66	83	63	72	70	74	88	71	71
Ratio Mix (Adhesive/Hardener)	40/100	70/100	30/100	100/100	80/100	50/100	70/100	90/100	80/100	80/100
Glue Spread (lbs/Mft^2)	85	82	92	75	85	85	73	100	80	80
Size Lumber (inch x inch)	2x4	2x8	2x8	2x4	2x4	2x4	2x4	2x6	2x4 & 2x6	2x4 & 2x6
Assembly Time	56 min.	44 min.	40 min.	21 min.	45 min.	42 min.	21 min.	38 min.	38 min.	45 min.
Panel Size (ft x ft)	7x18	7x18	7x18	7x18	7x18	8x24	8x12	8x18	8x18	8x18

2.3.2 Observed reported issues with processing narrow boards from small logs at D.R. Johnson

The lumber from both sources was included in the cores of CLT panels produced at D.R. Johnson. Once the material reached D.R. Johnson, three boards could not pass through the finger jointer due to rot and were removed from production (Lawrence and Brock 2017).

The next adjustment for our test material, was a lengthened layup time. This was a result of using 2x4s instead of the company's standard 2x6 lumber being used as laminations. Smaller pieces of lumber results in additional pieces for the same layer area, compared to using 2x6s, that need to be handled to layup an entire panel. More handling equates to more time needed and thus longer layup periods for the panels.

Due to the presence of twist some pieces of lumber could not be properly flattened in the planner and thus was not consistently planed (Figure 34). This means that some pieces of lumber were planed thinner than the target. The effect of loose thickness tolerances due to planing overly twisted pieces was explained in section 1.8.5 Thickness Tolerance and can be seen in Figure 34 where a piece of lumber was planed too thin causing a gap within the core of the panel. This is a major issue because the adhesive line in this spot (and possibly along the lamination) was not pressed properly.

Due to the substantial presence of twist, the panels had to be manually pressed down to be loaded into the pneumatic press (Figure 31). According to the CLT line team this, difficulty in loading the press was not typical. The twist was present only in the lumber that was processed from the Malheur restoration material and most likely resulted from large amounts of juvenile wood.

Figure 34: Due to bow and twist, when sent through the planer, the lumber becomes too thin for panel production and/or a sufficient bondline.

2.3.3 Panels with restoration fiber in all layers

Three and five-ply homogeneous panels consisting of Ponderosa pine, White fire and Douglas-fir were produced to detect and separate the potential effects of individual species on the adhesive bond integrity in the layups with mixed species in the core.

Material received from Collins Co. was graded as utility grade. Collins Co. does not procure Douglas-fir. Consequently, the panels consisted of Ponderosa pine and White fir in the core layers, with the face layers being produced from D.R. Johnson Douglas-fir lumber. CLT panels produced using Collins Co. lumber was used only for mixed species panels and no homogeneous CLT panels, as the required amount of homogeneous panels were already acquired. D.R. Johnson did place some of their own 2x8 Douglas-fir material at the ends of the panel, which would then be trimmed off when the panels were CNC'd. This was done with the understanding that the focus of the study was not on D.R Johnson's material, but on the material removed in thinning from the national forest.

Lumber from Collins Co. is typically dried to 15% moisture content (MC), but the company does not guarantee the MC of individual pieces. Due to the tight schedules of the production of D.R. Johnson, there was no opportunity to measure the MC of incoming pieces at the time of lamination. However, upon arrival at OSU, the moisture content was checked on ten randomly selected locations of the CLT panels and were found to be in accordance with 12 ±3% and calculated using a Delmhorst RDM-3 moisture meter which was adjusted for each species analyzed. We did not receive a panel production summary (as seen in Table 2) for the panel produced with Collins Co. lumber. These panels were processed January 17-18, 2017.

2.4 Transportation

One of the assumptions of this project was that the emergence of sawmills capable of processing small diameter logs and CLT manufacturing operations in the region is a sign of a trend, and that the density of such operations in the future will increase. At the time of the project the distances the harvested material had to be transported was much further apart than what is commonly seen within the lumber industry. However, while not common, D.R Johnson currently gets lumber meeting the requirements for their CLT line from as far away as Idaho. The company is attempting to find lumber sources closer to their Riddle, OR facility. The economic impact of the transportation from Iron Triangle to Idaho Forest Group to D.R. Johnson was analyzed in a parallel study (Lawrence 2017). The transportation done by Collins Co. was donated time and effort. Figure 10 shows the path the material traveled.

2.5 Tests and testing procedures

To determine the technical feasibility of hybrid CLT panels with forest restoration material in the core of structural CLT panels, the 3- and 5-ply layup specimens were subjected to qualification tests per ANSI\APA PRG 320-2012 production standard. The qualification tests focused on bond integrity of the products. In addition, bending test on beam specimens extracted from the test panels, were conducted to determine basic engineering characteristics on the test layups. Test results were compared with benchmark values specified for PRG 320-2012's prequalified E3 grade. The f_b (or MOR) and E of the test material was determined in 3rd-point bending test and f_v (nominal shear stress) determined on short span bending. The bond integrity of the test panels was qualified per PRG 320-2012 via block shear test (layups must pass with ≥80% WF criteria) and cyclic delamination test (layups must pass ≤5% delamination criteria).

2.5.1 PRG 320-2012 qualification test methods considered in this project

Material characteristic tests (to determine E and f_b) were performed according to the ASTM D198 standard. Minimum qualifications set by the PRG 320-2012 were performed according to the standards AITC T107 and T110 tests.

2.5.1.1 Engineering characteristics

Engineering characteristics (f_b, E, and f_v) were determined by testing the material in a Third- and Center-point bending flat-wise tests. These tests were based on the standard ASTM D198 methods:

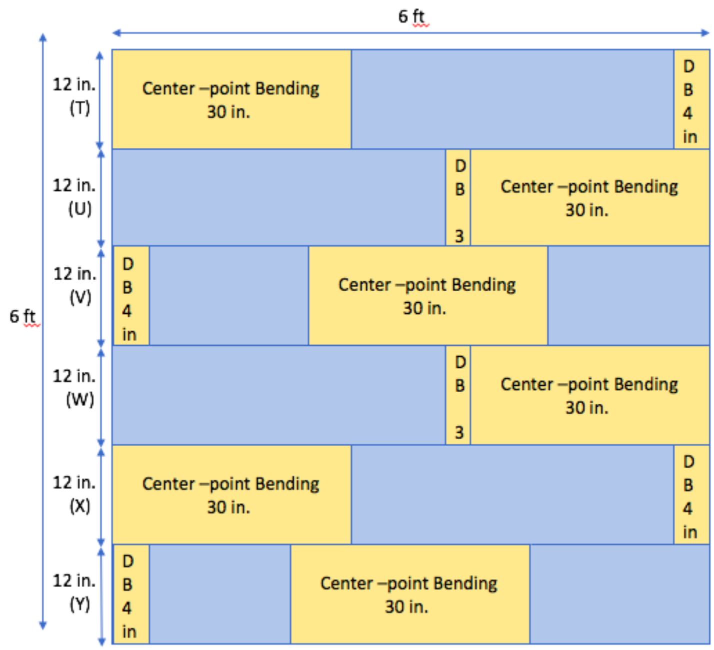
- Bending flat-wise: Third-Point loading (per ASTM D198-15)
- Bending flat-wise: Center-Point loading (per ASTM D198-15)

2.5.1.2 Bond integrity

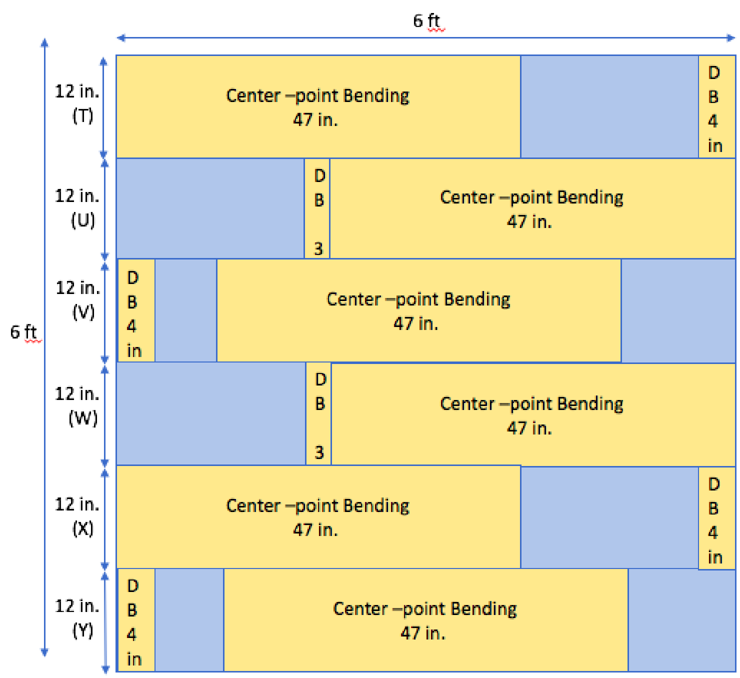
Cyclic delamination and Block shear tests were performed to determine if the material passed the minimum qualifications required by the PRG 320-2012. The tests were done according the AITC T107 and T110 methods:

- Block shear test (ASTM D905 referred in AITC Test T107-2007)
- Cyclic Delamination test (per AITC Test T110-2007 referred in AITC 190.1-2009)

2.5.2 Specimen fabrication

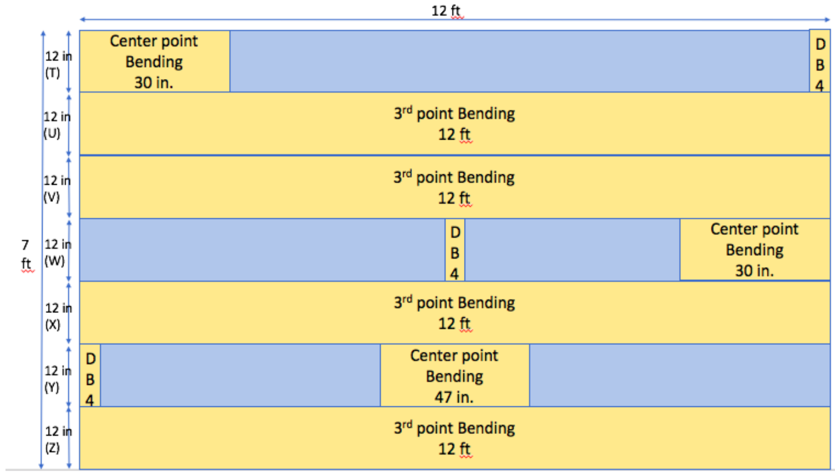


(a)

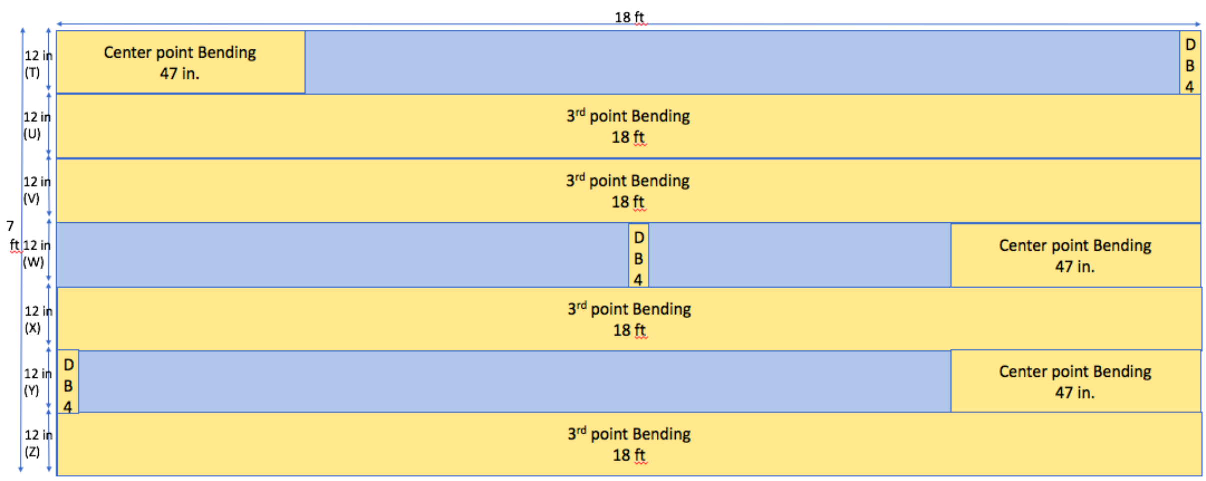


(b)

Figure 35: The cut pattern for a 3- (a) and 5-ply (b) single species panel. Where "DB" refers to strip of material that was cut for further breakdown in the cyclic delamination and block shear specimens. The DB (4") cuts are to ensure the sample is not effected by any inconsistencies that occurred along the edge of the panel.



(a)



(b)

Figure 36: The cut pattern for a 3- (a) and 5-ply (b) mixed species panel. Where "DB" refers to strip of material that was cut for further breakdown in the cyclic delamination and block shear specimens. The DB (4") cuts are to ensure the sample is not effected by any inconsistencies that occurred along the edge of the panel.

The material matrix used for this project was based on the specific species mix of the processed restoration material removed by Iron Triangle and Collins, as explained in 2.1 Raw material source. The sample matrix consisted of nine sample groups (three tested in bending properties (E and f_b) and all nine tested in shear (f_v) block and delamination): 3-ply and 5-ply Ponderosa pine *(Pinus ponderosa)*; 3-ply and 5-ply White fir *(Abies concolor)*; 3-ply and 5-ply Douglas-fir (*Pseudotsuga menziesii)*; 3-ply Mixed species and two different 5-ply Mixed species panels, one created all out of material generated by the Iron Triangle and one with Collins Co. material in the core of the panels. Each group consisted of three panels. This matrix resulted in a total of 27 panels grouped as seen in Table 3. The single species Douglas-fir panels made with D.R. Johnson CLT lumber stock. Where used as the control for the project.

Single species panels were produced to isolate potential bonding problems generated by an individual species and to see if each species could meet the PRG 320-2012 qualifications independently. Therefore, the homogeneous species panels were not tested in 3rd-point bending as this study was focused on the hybrid mixed species panels.

The homogeneous species panels were made smaller than the mixed species panels; as a result, D.R. Johnson combined the sets of three homogeneous species panels into one large 7'x18 foot panel before being broken down by the Hundegger PBA into the three smaller panels (Figure 37).

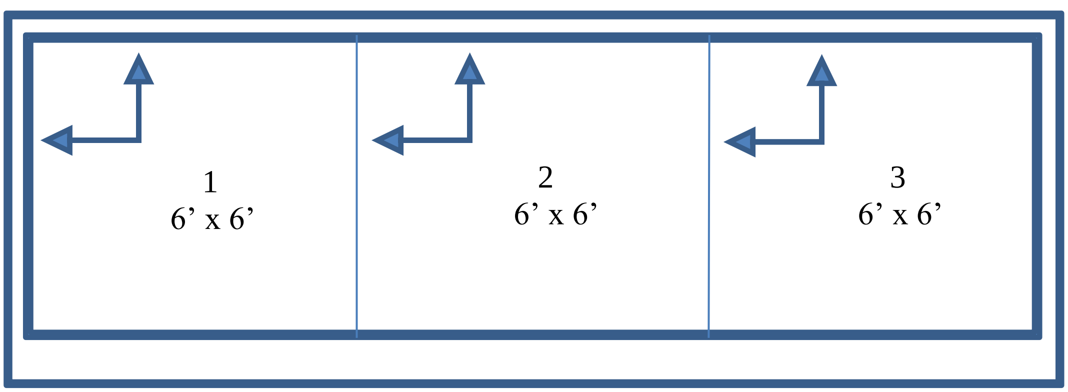


Figure 37: The homogeneous species panels were combined into one large 7'x18' panel and then was later broken down into three 6'x6' panels by D.R. Johnson's Hundegger PBA.

The combination of the three panels is not allowed by the PRG 320-2012 for prequalification samples. It is indicated within the PRG 320-2012 (Section 8.2.1 and 8.2.4) that, "A minimum of two replicate CLT pre-qualification panels shall be manufactured for pre-qualification…Six square/rectangular specimens (three for block shear tests, i.e., "B" specimens and three for cyclic delamination tests, i.e. "D" specimens) shall be extracted from each pre-qualified panel…" (ANSI 2012). The decision to combine the panels was taken by DR Johnson without confirmation from OSU.

Table 3: Panel matrix used, with total number of each type of panel produced.

**These panels were combined and cut from one 7'x18' panel.*

Panel Construction and Species	**6'x6'**		**7'x12'**	**7'x18'**
	3-ply	5-ply	3-ply	5-ply
Douglas-fir (Control)	3*	3*		
White fir	3*	3*		
Ponderosa pine	3*	3*		
Mixed core			3	3
Mixed species				3

The number of specimens per sample group and test are summarized in Table 4.

As it was only the species being changed during production (PRG 320-2012 section 8.2.1), only two panels for each combination were needed to satisfy the PRG 320-2012, but three replicates for the project were made. The additional specimens allowed for improved statistical significance of the outcomes. For determination of mechanical properties, a sample size of greater than 10 is needed for coefficient of variances (COV) greater than 13%. A sample group of 12 for the third-point bending was produced from the Mixed species panels, while 9 specimens for center-point bending tests were produced from the same panels.

Table 4: Number of samples per sample group and test.

Panel	Benchmarks (Bending tests)				Min. Qualifications (Bond Integrity tests)			
	3rd- point		Center-point		Block shear		Cyclic Delamination	
	3-ply	5-ply	3-ply	5-ply	3-ply	5-ply	3-ply	5-ply
Douglas-fir (Control)	n/a	n/a	18	18	18	18	18	18
White fir	n/a	n/a	18	18	18	18	18	18
Ponderosa pine	n/a	n/a	18	18	18	18	18	18
Mixed core	12	12	9	9	9	9	9	9
Mixed species	12	12	9	9	9	9	9	9

2.5.2.1 Pre-cut at D.R. Johnson Hundegger PBA machine

The specimens were pre-cut at D.R Johnson on their Hundegger PBA CNC. The use of the new CNC machine sped up the cutting process. All cut patterns for the panels, with dimensions, can be seen in Figure 35 and Figure 36. The 3rd-point bending specimens and the center-point specimens were instantly tested when delivered to OSU as not additional prep work needed to be done before testing. The block shear and delamination samples were stored in an ASTM standard conditioning room. The project's cut pattern would have required a full (8-hour) day per panel before the Hundegger PBA CNC was added to the production line, but only equated to roughly 30-45 minutes (dependent upon the panel depth) afterwards at D.R. Johnson. Then each piece of the broken-down panels were labeled with a unique code (Table 5), wrapped and then shipped to OSU.

Table 5: Specimen code definitions for CLT samples.

Code	Definition
D	Douglas-fir panel
P	Ponderosa pine panel
F	White fir panel
M	Mixed species panel
A	3-ply panel
B	5-ply panel
1, 2, 3, 4, 5, 6	1 of 3 panels produced per sample group; mixed species panels produced by Collins Co. were numbered 4-6.
T, U, V, W, X, Y, Z	Location of sample in panel, which starts at the top of the panel and goes down the height of the panel in 12 inch increments.

After testing was completed, 3rd-point and center-point bending samples were broken down and recycled, as they were too large for long-term storage.

2.5.2.2 Fabrication of block shear and cyclic delamination specimens at OSU

Cyclic delamination and shear test specimens needed additional fabrication. The cyclic delamination specimens were cut down into 3”x3” blocks through the thickness of the panel and block shear specimens were cut in a stair step pattern. The block that was initially cut from the larger panels at D.R. Johnson were 3”x12” or if the sample was on the edge of a panel 4”x12”. The blocks cut from the panels for the cyclic delamination and block shear specimens were cut with an additional inch of width when cut on the edge of the panel to prevent an incomplete sample, as the edges of the panel had overhang (as seen in Figure 29).

The section cut from the CNC machine (3”x12” or 4”x12”) was cut into four 3”x3” sections. Two of the four sections that were cut were set aside as spare samples, one 3”x3” block was used for cyclic delamination and one was further broken down for block shear analysis (Figure 38). Cyclic delamination specimens did not require any further processing once broken down into the 3”x3” block.

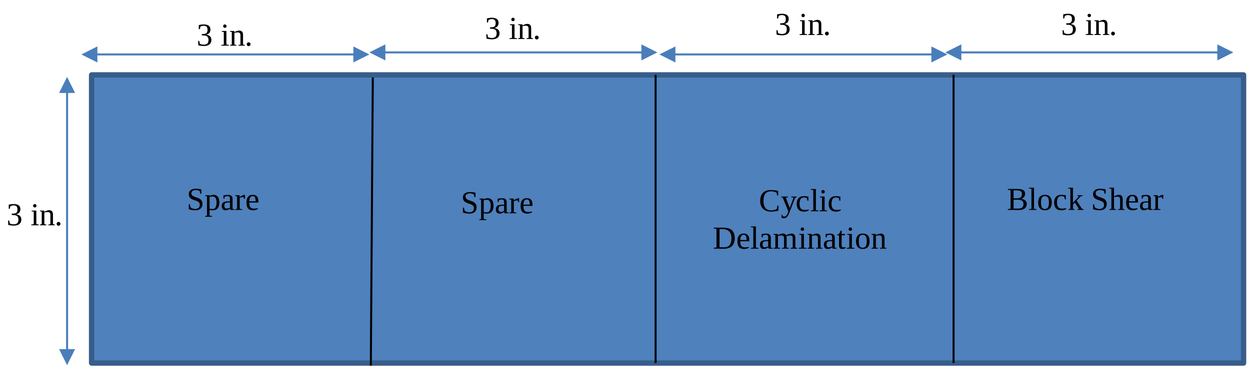


Figure 38: A diagram of the specimen cut up from the CNC generated blocks.

The block shear specimens were cut to have a shear plane of 1.75x2 inches and can be refered to as a “Stair Step” pattern (Figure 39). To produce the specimens, the 3”x3” were broken down using a band saw and a guiding block for specimen consistency (Figure 40). The specimens needed to be cut down the length of the specimen blocks (indicated by the dotted line in Figure 41), starting from the cut furthest in and working outwards. Once the specimens were cut lengthwise, the excess material could be sawn off at the desired bondline.

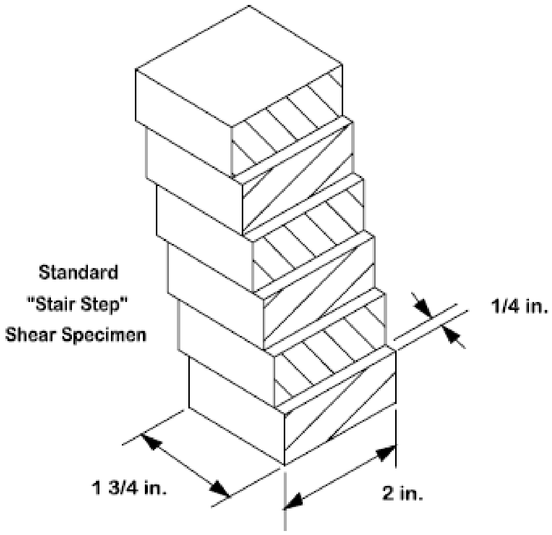


Figure 39: The stair step pattern that was used for the shear samples.

Figure 40: Sizing block used for consistency, lined up with a band saw, when producing the stair step block shear test specimens.

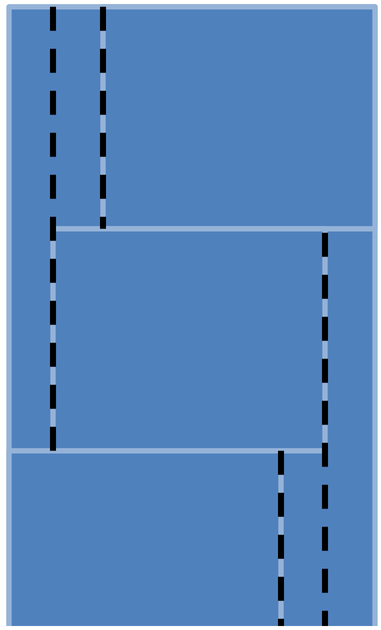


Figure 41: Cut diagram of block shear specimens to make the stair step pattern.

2.5.3 Tests Procedures and Measurements

Bending tests were aimed at determining the basic engineering characteristics of the test layup (elastic modulus (E), bending strength (f_b) and shear strength (f_v)). The measured values were then compared with benchmarks for ANSI/APA PRG 320-2012 pre-defined CLT grade E3.

2.5.3.1 Bending tests

Third-point bending:

Deformation of elastic modulus (E) and bending strength (f_b) was only performed on mixed species panels. The third-point bending tests were performed in accordance with ASTM/APA PRG 320-2012 section 8.5.3, which referrers to ASTM D198-15. The objective was to determine elastic and strength properties and to compare the tested material to the PRG 320-2012 predicted E3 CLT grade requirements. The specimens had a span-to-depth ratio of slightly more than 30:1. Subsequently, the beams fabricated from 3-ply panels had a length of 12 feet (144 inches), width of 1 foot (12 inches) and depth of 4 1/9 inches and the 5-ply beams fabricated had a length of 18 feet (216 inches), width of 1 foot (12 inches) and depth of 6 7/8 inches; an additional 6 inches in length on either end is included for overhang during testing. Bending flatwise in third-point loading was conducted in a Tinius Olsen frame with an MTA actuator, with a 40-kip load capacity.

The deflection in the center of the beams was measured with a linear variable differential transformer (LVDT) sensor. The sensor was mounted on a yoke supported at the neutral axis of the beam (Figure 42). Due to the extended length of the five layer panels, the yoke spanned only the center third of the panel (Figure 43). This is contrary to what is typically done where the sensor spans the entire length of the sample, but was accounted for in calculations of the modules by calculating the total deflection of the beam by adding the LVDT measurement from the center span and the deflection of loading points measured from the cross-head position. The combined defection measured by the LVDT and the cross-head was then used to calculate E_f with Equation 3 below.

The tests were subject to loading in displacement control mode at a ramp rate of 0.5 inch/min. The recorded loads and deflections were then used to calculate the modulus of rupture (MOR) and the modulus of elasticity (E_f) of the test beams. For determine initial test parameters, two samples were loaded at a ramp rate of 0.25 inch/min.

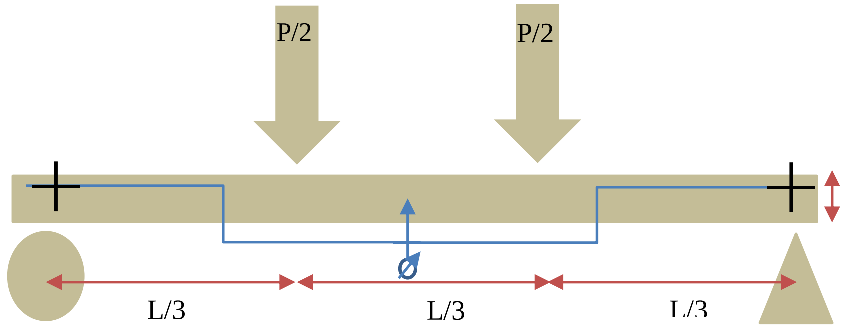


Figure 42: Third-point bending set up for 3-ply (12 foot) panels. The blue center arrow indicating where the LVDT was placed and measurement taken on the sample.

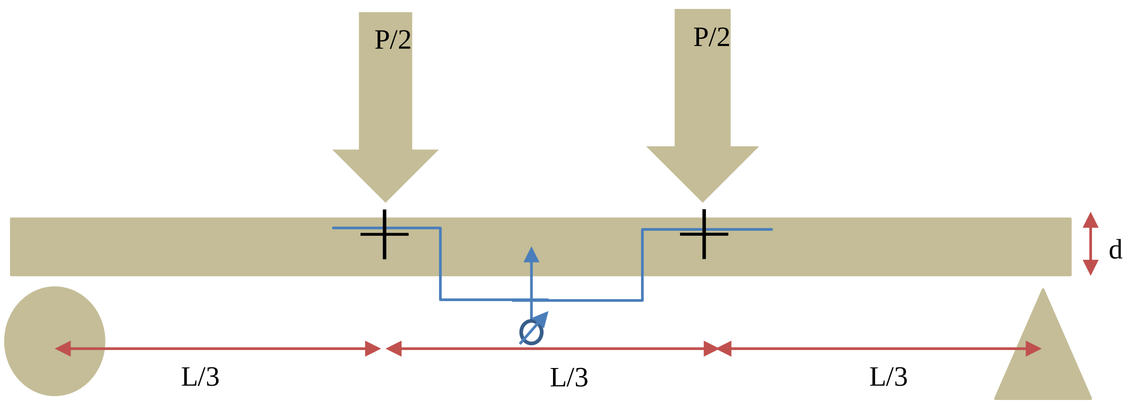


Figure 43: Third-point bending set up for 5-ply (18 foot) panels. The blue center arrow indicating where the LVDT was placed and measurement taken on the sample. Due to the length of the samples it was found easier to use a shorter LVDT span.

The MOR, or f_b, was calculated using the equation (Equation 2 from Table X2.1 of ASTM D198):

$$f_b = \frac{P_{max} L}{bd^2}$$

Where:

f_b = modulus of rupture (psi)
P_{max} = maximum load (lbf)
L = span (inch)
b = width (inch)
d = depth (inch)

While the E_f for the 3-ply panels was calculated with the deflection used from the LVDT sensor running the length of the sample (Figure 42), the 5-ply deflection was found using the sum of the deltas (combining the deflection found by the center- spaning LVDT sensor and the cylinder used to apply the top force). The E_f was then calculated using the equation (Equation 3 from Table X2.1 of ASTM D198):

$$E_f = \frac{23L^3}{108bd^3}\left(\frac{P}{\Delta}\right)$$

Where:

$$E = \text{modulus of elasticity (psi)}$$
$$P = \text{max load (lbf)}$$
$$L = \text{span (inch)}$$
$$\Delta = \text{central beam deflection}$$
$$b = \text{width (inch)}$$
$$d = \text{depth (inch)}$$

$(\frac{P}{\Delta})$ is the slope of the linear portion of the load-deflection diagram. Both equations are found in the ASTM D198 Table X2.1 (D07 Committee 2015a).

Center-point bending

The center point bending test was conducted according to ASTM/APA PRG 320-2012 section 8.5.5. Which refres to the ASTM D198 "Bending Flatwise-Center Point Loading" (test setup seen in Figure 44) (D07 Committee 2013). With the approximate span-to-depth ratio of 6:1 the beams fabricated from 3-ply material had a span of 30 inches, a width of 1 foot (12 inches) and a depth of 4-1/9 inches and the beams fabricated from 5-ply has a span of 47inches, a width of 1 foot (12 inches) and a depth of 6-7/8 inches; these sample lengths included an additional 4 inches to accommodate a 2-inch overhang on either side of the span to ensure safety of testing (making specimens 30 in. in length for 3-ply and 47 in. for 5-ply). The tests were also conducted in the Tinius

Olsen fram described in the previous section. A ramp rate of 0.1 inch/min was used to accommodate the shorter spans.

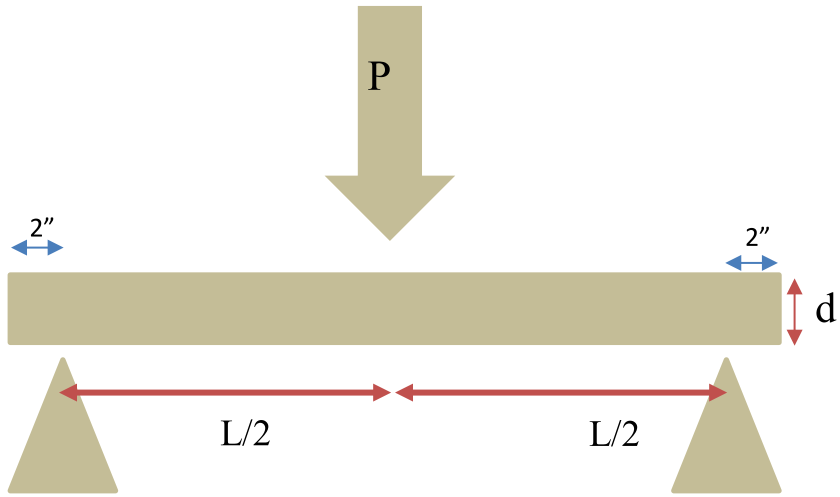


Figure 44: Short span setup. The samples were given a two-inch overhang and the orange braces were used to ensure that the samples were consistently placed in the sample location.

Nominal shear strength formula specified by the PRG 320-2012

$$f_v = \frac{3\ P_{max}}{4\ bd}$$

Where:

$$P_{max} = \text{maximum load (lbf)}$$
$$b = \text{width (inch)}$$
$$d = \text{depth (inch)}$$
$$f_v = \text{shear stress (psi)}$$

The ANSI/APA PRG 320-2012 does not provide any specific formulat for calcuation of a realistic shear stress for a layered composite section. Instead, ASTM D198 is referred, which provides a simplified shear stress formula for homogeneous sections. This formula was then used in calculations in this study, with the understanding that it provides only nominal shear strength, not reflecting the actural stress in the CLT sections. The equation (equation 10), used to determine shear strength, can be found in Table X2.1 of ASTM D198 (D07 Committee 2015a).

3.5.3.2 Bond Integrity Tests
Shear resistance by Block shear test:

The Block shear tests were performed according to the ANSI/APA PRG 320-2012 8.2.5 which follows the AITC Test Methods for Structural Glued Laminated Timber, Test T107-2007 “Shear Test” (AITC 2008). The testing apparatus and specimen placement can be seen in Figure 45. The samples were conditioned in a conditioning room at 20 ºC with 65 % relative humidity, and then individually removed from the room for testing. Therefore, the moisture content of the material was assumed at 12%.

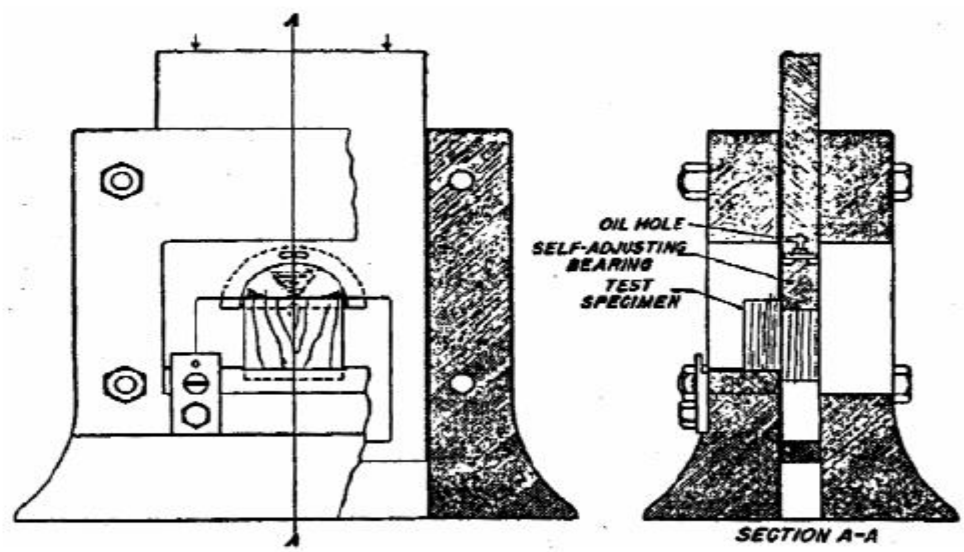


Figure 45: An example of the testing apparatus that was used and the placement of the samples within the device. (D07 Committee 2015c)

The tests were conducted on an Instron frame (model 5582Q5749) with a load cell range of ±22480 lbf (±100 kN); resolution of ±1.0e-3 N and Bluehill 2 software package which allowed automatic data aquasition.

The basic test procedure was as follows (Larkin 2017):

- Measure bondline area
- Place samples into test apperatus (Figure 45)
- Preload sample to 0-150 N
- Load to failure
- Analyze the fracture plane for wood failure percentage

The measurement of the specimen shear plane area was done with a Mitutoyo ABSOLUTE CD-6”CX caliper with a precision of ±0.01mm. The standard that was used, AITC T107, does not specify a ramp rate so ASTM D1037-12 section 20.4 was consulted. ASTM D1037 Section 20.4.1 specifies a ramp rate of 0.024 in/min (0.6 mm/min) ±50%. Since the results of the test are focused on the wood failure and not the shear strength, the samples were tested with a ramp rate of 0.035 inch/min (0.9 mm/min) (D07 Committee 2015b).

The specimens were then analyzed for the percentage of wood failure in the fracture plane. In order to increase the contrast between wood and the transparent MF resin the fractured areas were brushed with 0.5% safranin stain. The excess stain was blotted off with a paper towel. This method was found to be effective in a previous project dealing with another type of clear resin (Larkin 2017). Once stained, the fracture planes were photographed (Figure 46) with the specimen ID number. Photos were taken using a Nikon D3300 DSL camera with 24.2 megapixels (pixel area of 15.13 μm^2)

(Nikon 2015). The images were then processed with an imageJ software package (IJ 1.46r) by the National Institutes of Health (Ferreira and Rasband 2012) using a script created specifically for this purpose (Sept 2015). The program converts the color bondline image pixels in to greyscale and then counts the darkest pixels, which are representative of wood failure (Figure 47).

To calculate the wood failure, the amount of pixels qualified as "wood" based on the grayscale intensity value in the image was divided by the total amount of pixels in the bond area (Larkin 2017).

Wood failure was calculated as follows:

$$WF_i = \frac{p_w}{p_w + p_a}$$

Where,
WF_i=wood failure percentage of bond area "i"

p_a=number of pixels that are qualified as adhesive
p_w=number of pixels that are qualified as wood

This script was originally adjusted for PUR adhesive and for this project had to be re-adjusted for the MF resin that was used (the adjusted code can be seen in Appendix B).

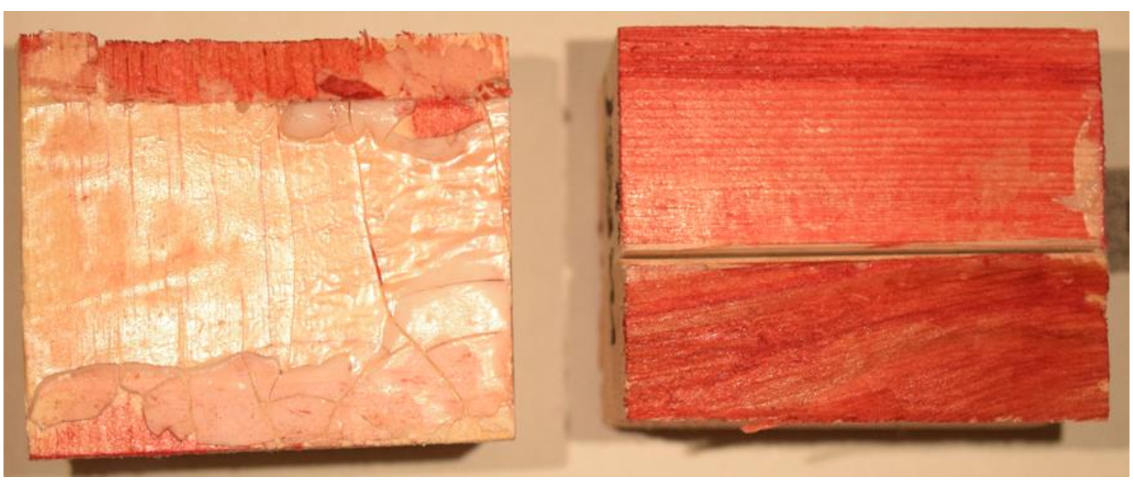
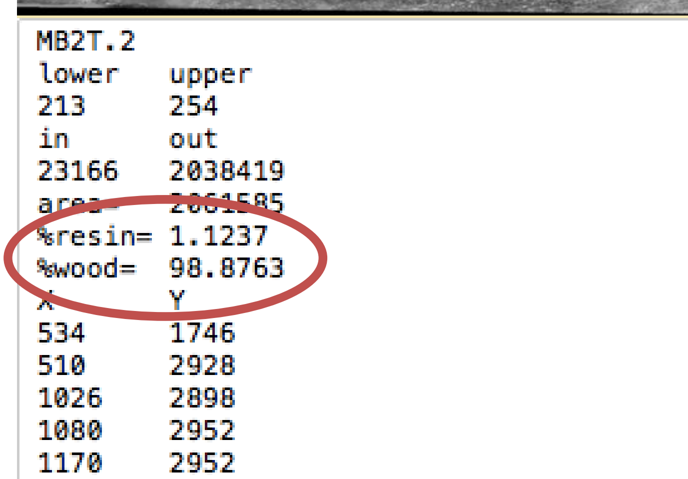


Figure 46: Sample with 0.5% Safranin stain to differentiate the wood failure from the resin failure.

(a)After the sample is stained and photographed, such as Figure 46. The image is then selected in ImageJ and selected side of the bondline is cropped.

(b) Once the image is cropped, it is set to gray scale with an adjustable scale to adjust if appropriate.



MB2T.2	
lower	upper
213	254
in	out
23166	2038419
area=	2061585
%resin=	1.1237
%wood=	98.8763
X	Y
534	1746
510	2928
1026	2898
1080	2952
1170	2952

(c) The program will then give the results, similar to those seen to the left. The amount of resin and wood failure are upfront and clear, indicated with the red circle.

Figure 47: The process of image analysis that was done on the shear samples after testing, with correlating descriptions (a), (b), (c).

While safranin stain did work well for most specimens, some issues were experienced when individual cells attached to the adhesive surface making it difficult to determine whether a sample passes the qualification criteria. It is sometimes difficult to properly qualify the failure automatically without a microscopic inspection of the surface. An example of when using the safranin stain could be difficult is with small transitions between the wood and glue failures, as seen in Figure 48.

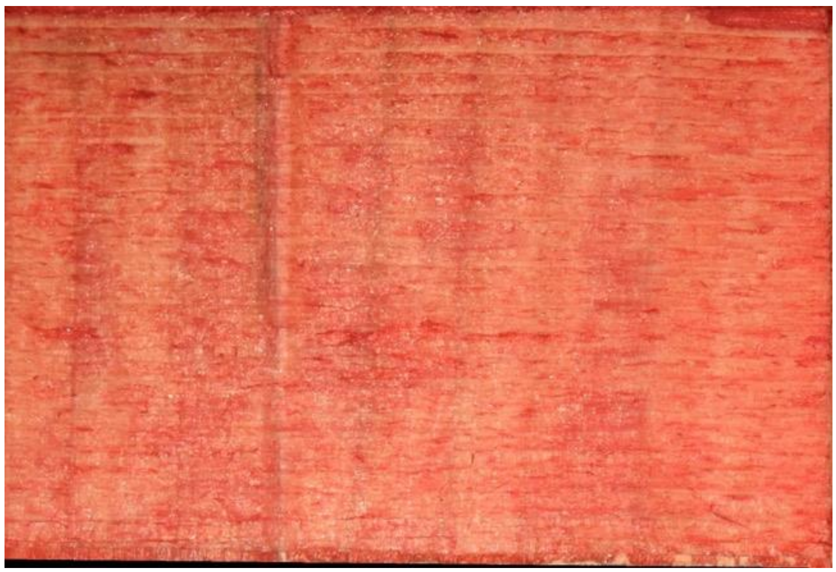


Figure 48: Example of some of the difficulty with safranin stain; where wood failure is present but minor, making it difficult to distinguish from the resin failure.

In Figure 48, there was minimal wood failure according to the ImageJ script used, but in reality, there was a higher level of wood failure. The grain orientation in Figure 49 resulted in the same miss-interpretation of the WF% from the images. Grain orientation of the area being stained affects the adsorption or stain intensity, which can register as resin failure even when the visual inspection would reveal only wood failure. This problem can be seen in Figure 49, highlighted with the blue circle. While the programing script was used to analyze the samples, it can be manually adjusted for specimens that were difficult to interpret.

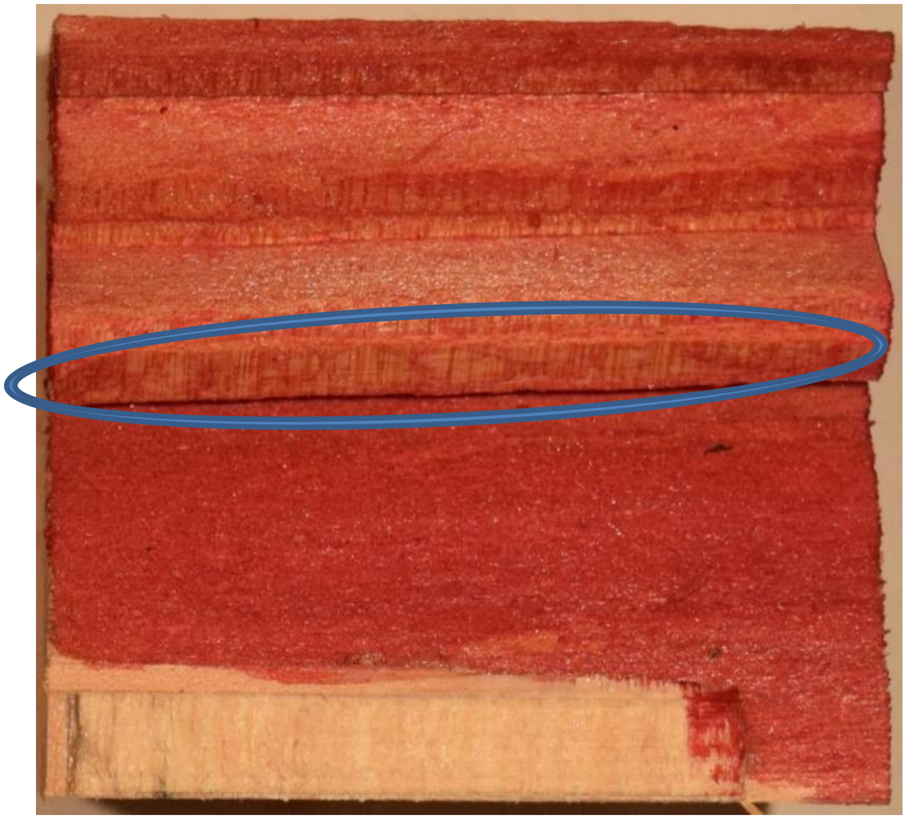


Figure 49: Another example of a difficulty using the Safranin stain. You can see where the cells in the radial direction do not adsorb the stain.

The illumination of the specimens was arranged in such a way that shadows were kept at a minimum. However, because the fracture places are not consistently flat, not all shadows could be removed and they may have been misinterpreted by the script algorithm.

In order to compare the accuracy of the script to that of the visual method, fifteen samples were randomly selected. The visual method consisted of visually sectioning the bondline into 12 equal rectangular regions of 0.5x0.5 in^2 using a clear gridded sheet. Each grid square is then estimated for wood failure (WF%) to the nearest 10%. A moveable fiber optic light source (Olympus LG-PS2-5), other overhead lights, and a magnifying glass of 2x and/or 6x are used for aid. The average WF% was then calculated. Each face was used in the evaluation for both the visual and computerized analysis.

This analysis can be seen in Figure 50, where "Human" represents the visual methods with the grid and magnifying glass, and "Computer" represents the optical method combined with the image analysis script. It shows that the computer analysis is somewhat more conservative than the visual method.

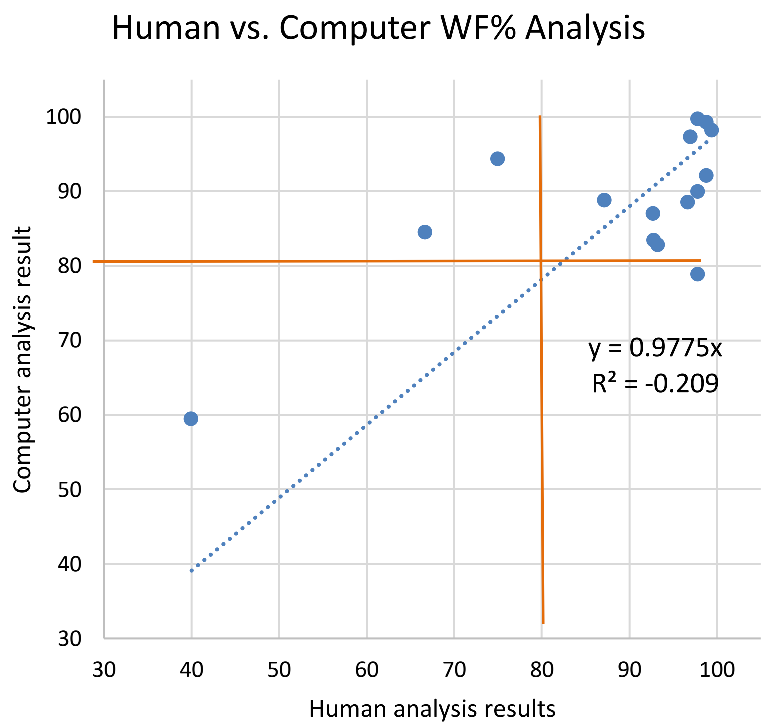


Figure 50: Graph showing the correlation between the computer-analyze samples and those that were analyzed by a human.

Cyclic Delamination Test:

The cyclic delamination tests were conducted in accordance with AITC T110-2007 "Cyclic Delamination Test". Test specimens were cut into 3x3 in^2 blocks, with thickness dependent on panel layers (3- and 5-ply or 4.12in. and 6.78in.). The test consisted of a single soak-dry cycle, followed by the assessment and measurement of the extent of delamination. The soak cycle was conducted using a vacuum/pressure vessel seen in Figure 52.

Mass of each specimen was recorded before the samples were placed in the vacuum/pressure vessel (Figure 52). The specimens were placed in a wire basket which allowed them to be submerged under water, during the cycle. Next, the speceimens were placed under a vacuum for 30 minutes at 22.5±2.5 in. of Hg (12.3±2.5 psi) and then pressurized for two hours at 75±5 psi (Figure 51). Once the vacuum/pressure cycle was completed, the samples were placed in an air-circulated oven set at 160±5 °F for 10 to 15 hours to dry. After the first 10 hours of drying, the mass of the samples was measured to see if they had redried to within 15% of their initial mass; if not, they were measured periodically until this criteria was reached. This step was repeated to a maximum of five more hours until the samples reached the target mass (within 15% of the original mass).

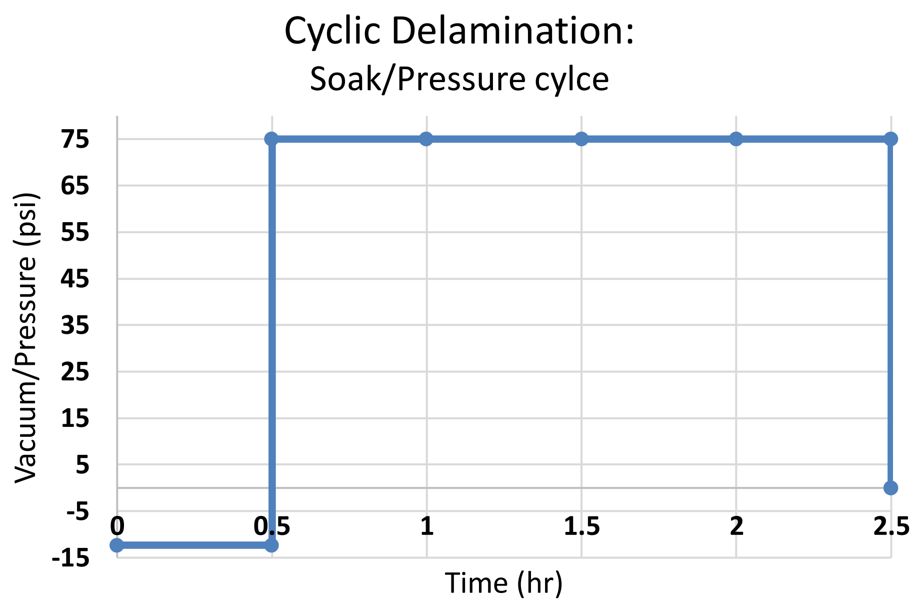


Figure 51: The cyclic delamination soak cycle time lapse.

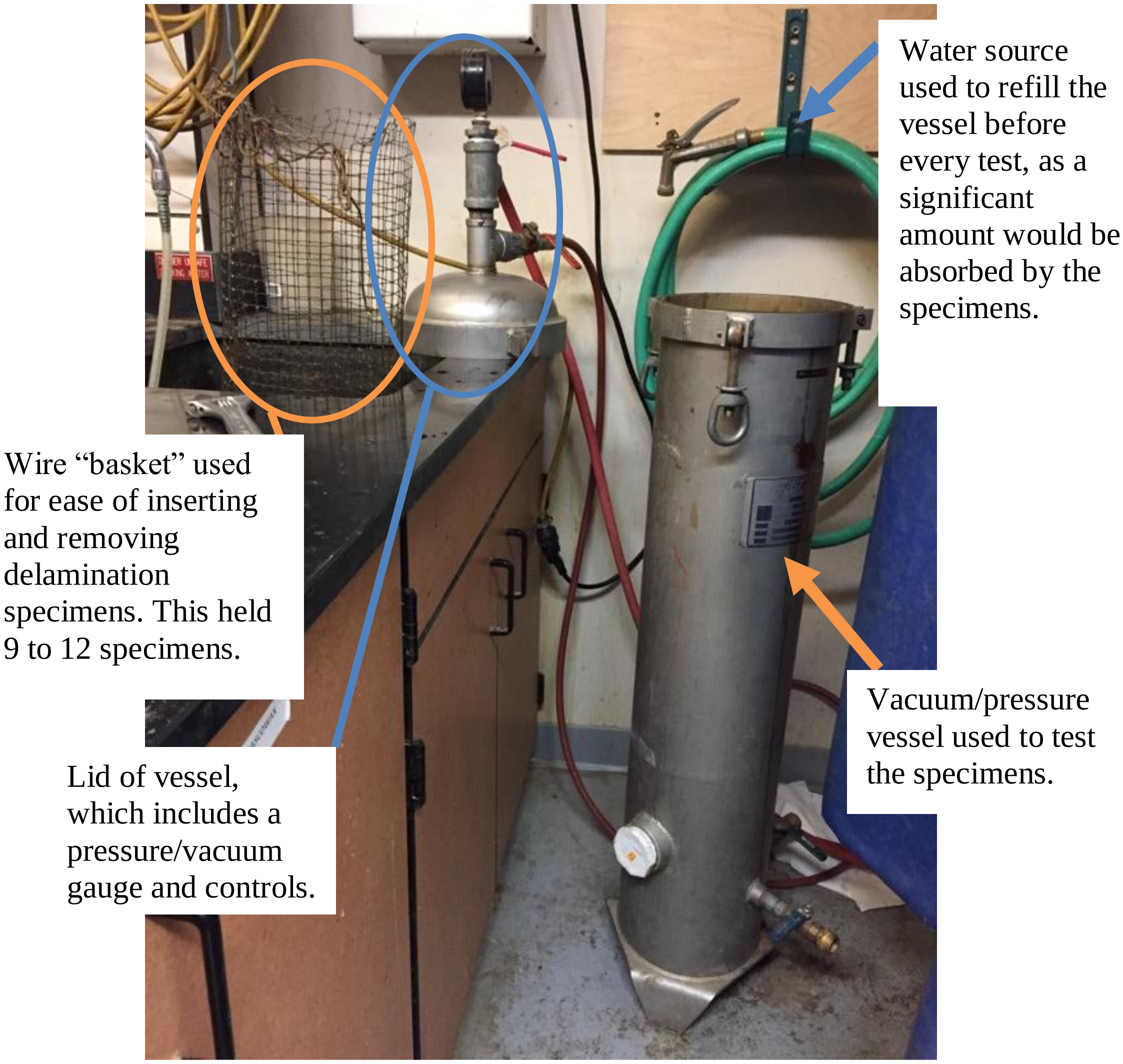


Figure 52: The vessel that was used for cyclic delamination testing. To the left in the sink, is the cage into which the specimens are placed into for ease of removal.

Summary of the steps of the process are as follows (Larkin 2017):

Vacuum/Pressure soak cycle

- Record sample’s initial mass
- Load and seal specimens in the wire basket and then into the vessel
- Pull a vacuum of 25±5 in. Hg (12.3 ± 2.5 psi) for 30 minutes
- Apply a pressure of 75±5 psi for 120 minutes
- Release vessel pressure
- Remove specimens and record wet weight

Drying cycle

- Load speciments into a preheated oven with circulating air at 160±5°F
- Dry for 10 to 15 hours
- Periodically measure samples until the mass is within 15% of the initial mass

Once the samples reached to within 15% of their original individual mass, they were immediately removed from the oven and measured for delamination using a ruler with a 1mm precision. Delamination is defined as the seperation of layers in a laminate due to failure of the adhesive either in the adhesive itself or at the interface between the adhsive and the adherend (ANSI 2012). Each bondline around the circumfrence of the specimen was measured and then delamination was calculated using the fraction of the total length in the bondlines of the sample. Each specimen must pass with ≤5% delamination in order for the entire sample group to pass the requirements.

The assessment of delamination was later confirmed on a sub-sample of the specimens by Chris Jennings, a Quality Auditor with the APA—The Engineered Wood Association.

CHAPTER 3: RESULTS

Results of the physical tests are summarized in the following sections. Bending characteristics (f_b, E, and f_v) are compared with ANSI/APA PRG 320-2012 benchmarks posted for the predefined CLT E3 grade. Bond integrity tests results (WF% and delamination) are compared with the PRG 320-2012 qualification criteria.

3.1 Apparent Elastic Modulus and Bending Strength

The long span beams mainly failed at finger joints and knots on the tensile side (Figure 53 and Figure 54). Test results by panel construction type are summarized in Table 6. Specimens made with No.2 Douglas-fir face and thinning core lumber exceeded benchmark characteristic set by the PRG 320-2012 for E3 CLT grade. The benchmark characteristic values were calculated based on the stiffness valued listed for the E3 CLT grade in Table A2 in PRG 320-2012. Both the mixed core and mixed species sample groups exceeded the characteristic values MOR (f_b) and E_f benchmarks for the E3 preset grade.

Table 6: MOR and E results for the 3- and 5-ply mixed species panels compared to that of the PRG 320-2012 E3 grade requirements. The samples seem to exceed the minimum requirements set by the current standards. The asterisk represents the panels that were produced completely with material that was harvested for the project and not No.2 visual grade Douglas-fir on the exterior layers.

Panel Composition		Test Results		PRG 320-2012 E3 Benchmark	Test Results		PRG 320-2012 E3 Benchmark
Ply #	Species	MOR (f_b, psi)	COV	MOR (f_b, psi)	E_f (E_0, psi, $x\ 10^6$)	COV	E_f (E_0, psi, $x\ 10^6$)
3-ply	Mixed core	4,700	11.1%	2,087	1.64	3.1%	1.17
5-ply	Mixed core	3,400	3.50%	1,706	1.38	8.09%	0.96
	Mixed	3,000	7.93%		1.05	11.7%	

Figure 53: Failure of a 5-ply third-point test specimen at finger joints and knots.

Figure 54: Failure of a 5-ply third-point test specimen at two finger joints, which were close together.

3.2 Shear strength determined by center-point bending

It should be noted that the formula in ASTM D198 referred by the PRG 320-2012 assumed a homogeneous section. Thus, calculated f_v is only an imperfect approximation of actual shear strength in a cross-laminated section.

In Table 7 it can be noted that both the homogeneous species and mixed species sample groups were tested for shear strength. All sample groups met the benchmarks for the E3 grade shear strength. The lowest mean value was recorded for 5-ply White fir (234 psi).

The PRG 320-2012 requires, for mechanical property qualifications, that a sample group of greater than 10 is needed for a COV greater than 13%. While 6 samples were produced from each of the single species panels (making 18 specimens per sample group), only 9 samples could be cut from the Mixed species panels, but this criterion was still met with COVs for the shear strength (f_v) ranging from 3.4-11.2% of the 3- and 5-ply panels.

Table 7: fv results for 3-ply panel groups compared to the predetermined PRG 320-2012 E3 grade requirements. fv results for 5-ply panel groups compared to the predetermined PRG 320-2012 E3 grade requirements.

Panel Composition		Test Results		PRG 320-2012 E3 Benchmark
Ply #	Sample Group	Shear Strength (f_v, psi)	COV (%)	Shear Strength (f_v, psi)
3-ply	Douglas-fir (Control)	352	3.8	106
	White fir	265	7.9	
	Ponderosa pine	300	5.3	
	Mixed core	338	11.2	
5-ply	Douglas-fir (Control)	273	5.0	75
	White fir	234	5.0	
	Ponderosa pine	275	6.4	
	Mixed core	273	3.4	
	Mixed species	255	5.3	

3.3 Bond integrity qualification tests

By the PRG 320-2012, to qualify for structural use CLT, material specimens must meet bond integrity criteria specified as shear resistance, assessed by wood failure percentage (%) in the fracture zone (greater than or equal to 80% wood failure on average (AITC T107)) and resistance to delamination assessed by the relative delamination in the specimen after one soak-dry cycle per AITC T110 (less than or equal to 5% delamination on an individual basis).

Table 8: Summary of the Shear block and Cyclic delamination tests.

Panel Composition		Shear block Test Results (Required)		PRG 320-2012 Minimum Qualification	Shear block Test Results (Supplemental Information)		Cyclic delamination Test Results (Supplemental Information)		PRG 320-2012 Minimum Qualification
Ply #	Sample Group	Average (WF %)	COV (%)	Minimum Wood Failure (WF) (%)	Shear Strength (psi)	COV (%)	Max. (%)	Average (%)	Maximum Delamination (%)
3-ply	Douglas-fir (Control)	90	*9.9*	≥ 80	106.7	26	4.9	0.76	≤ 5
	White fir	90	*9.5*		86.2	36	3.8	0.66	
	Ponderosa pine	**69**	***30.4***		90.5	39	***15.9***	***5.2***	
	Mixed	*87*	*15.1*		107.9	36	***16.9***	3.3	
5-ply	Douglas-fir (Control)	89	*12.9*		102.7	47	3.4	0.83	
	White fir	*90*	*9.7*		97.1	45	***19.6***	1.9	
	Ponderosa pine	*87*	*14.7*		107.7	35	***10.2***	2.3	
	Mixed core	*82*	*17.8*		88.1	43	***20.0***	***7.6***	
	Mixed species	*85*	*22.6*		94.4	43	***14.5***	4.1	

3.3.1 Bond resistance to shear by block shear test

Results of the block shear test are provided separately for shear strength and wood failure.

3.3.1.1 Shear Strength

Table 8 shows the average shear strength of each combination by panel composition. While, the PRG 320-2012 does not require this characteristic to be reported, it is listed here to provide a better understanding of the material.

3.3.1.2 Wood Failure Percentage

Average wood failure fraction in the fracture plane for each combination is listed in Table 8. The criteria set by the PRG 320-2012 is that all sample groups must have an average wood failure (WF) greater than or equal to 80% (≥80%) to pass. The only group that failed the criteria was the 3-ply White fir panels (69.2%) which is marked in red in Table 8. All combinations for the 5-ply panels passed. The coefficient of variance (COV) for the 3-ply Ponderosa pine is particularly high, layup specimens with Ponderosa pine had a wide range of failures, which caused the large COV of 30.4%. Removing the lowest WF% (9.83%) resulted in a still somewhat high COV of 26%. There were seven samples with a WF% of less than 50.

The samples group that did not meet the minimum qualification of an average of ≥80% wood failure is marked red in the Table 8.

3.3.2 Resistance to delamination

The PRG 320-2012 qualifications for cyclic delamination requires all the specimens in the evaluated group show ≤ 5% delamination after one soak-dry cycle. This means that each individual specimen must qualify with no more than 5% delamination, otherwise it results in failure of the entire group. Table 8 shows the summary cyclic delamination results for the 3- and 5-ply panel combinations. Only the reference laminations with Douglas-fir in all layers passed this criterion for both 3- and 5-ply specimens. 5-ply laminations with White fir also passed. For all other combinations, at least one specimen in the group delaminated more than 5%. Averages are reported to give a general understanding of the distribution of the test results; however, it should be noted that the distribution of delamination values were strongly skewed towards 0%.

Figure 55 through Figure 62 show the individual specimen results of cyclic delamination, where the red line indicates the 5% maximum delamination failure allowed on an individual specimen basis. The individual results are reported to ensure an understanding of the difficulty in passing the criteria.

Groups that failed and did not meet the PRG 320-2012 delamination criteria or E3 benchmark and marked red in Table 8. Combined results for 3- and 5-ply Mixed species panels with No.2 visual grade exterior layers compared to PRG 320-2012 qualification criteria and the E3 grade benchmarks can be seen in Table 9 in section 4.4.

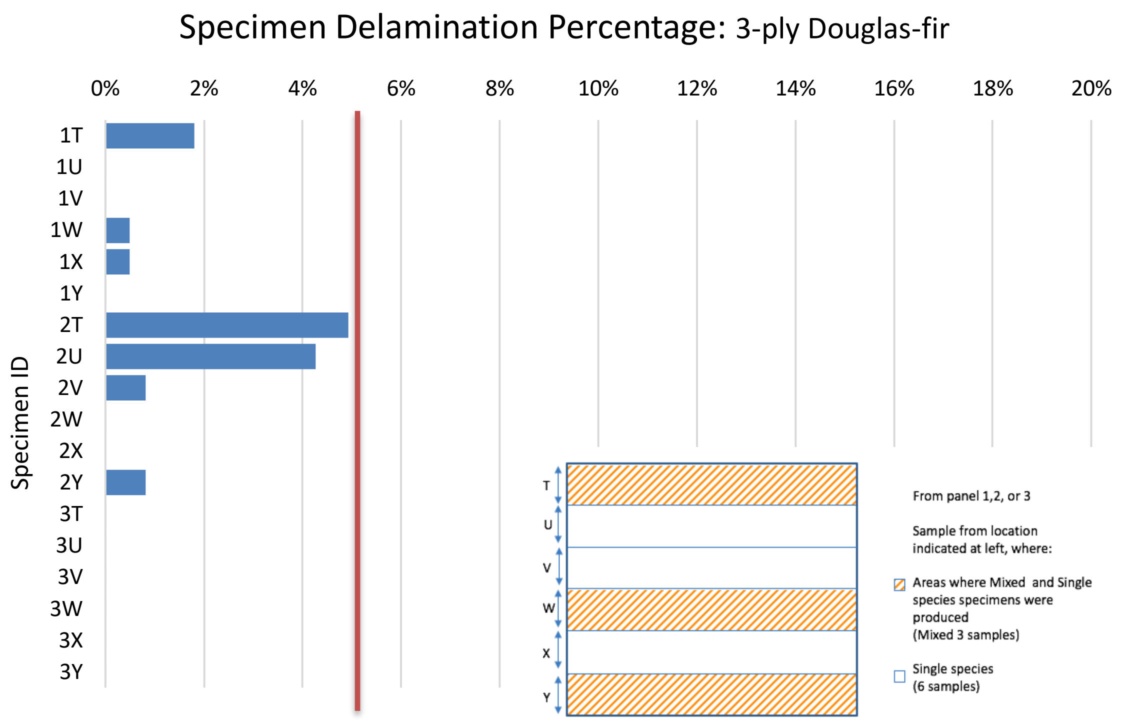


Figure 56:Individual cyclic delamination specimen results for the 3-ply Douglas-fir panels. The red line indicates the maximum delamination allowable.

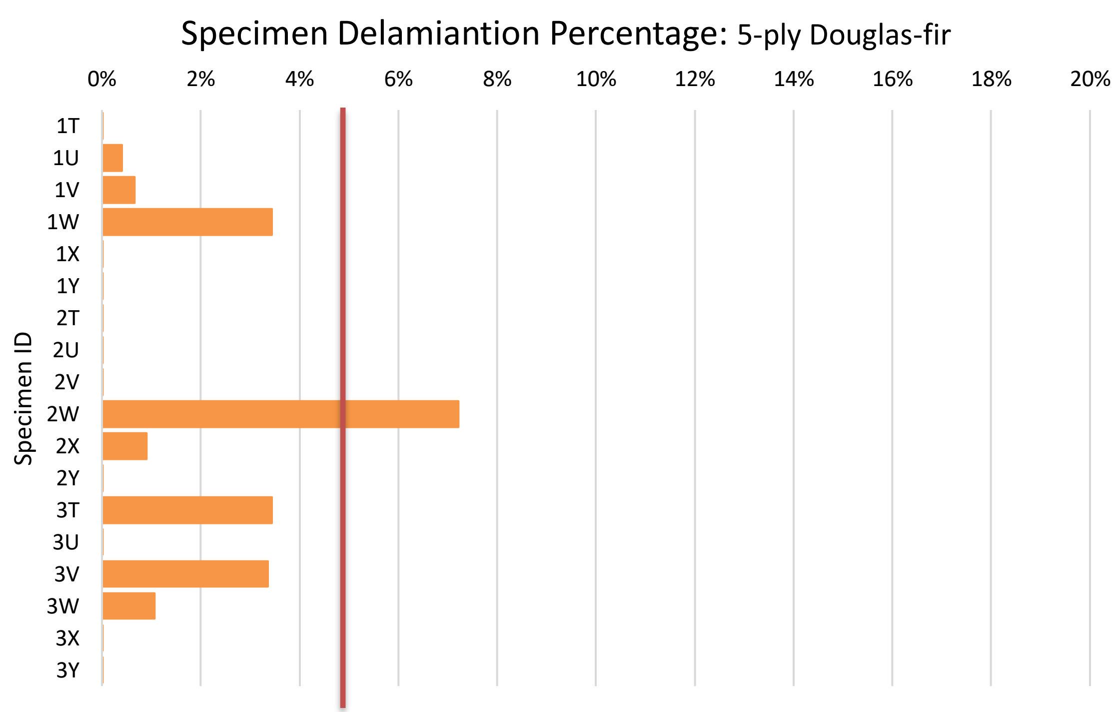


Figure 55:Individual specimen cyclic delamination results for the 5-ply Douglas-fir panels. The red line indicates the maximum delamination allowable.

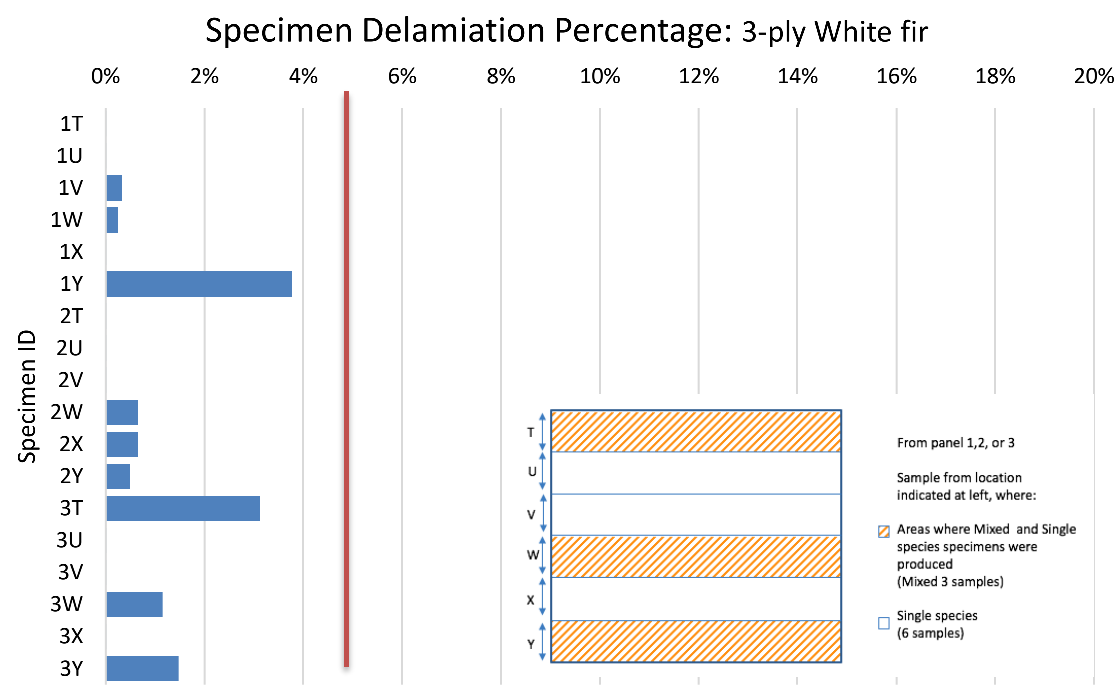


Figure 57:Individual specimen cyclic delamination results for 3-ply White fir. The red line indicating the maximum allowable delamination.

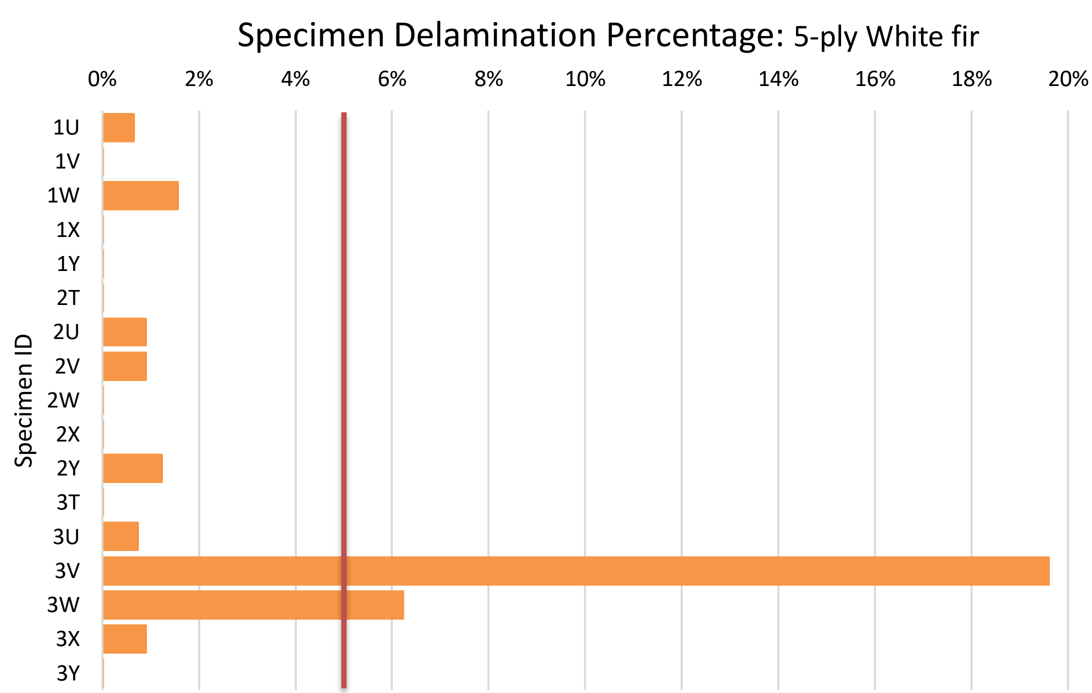


Figure 58: Individual specimen cyclic delamination results for 5-ply White fir. The red line indicates the maximum delamination allowable.

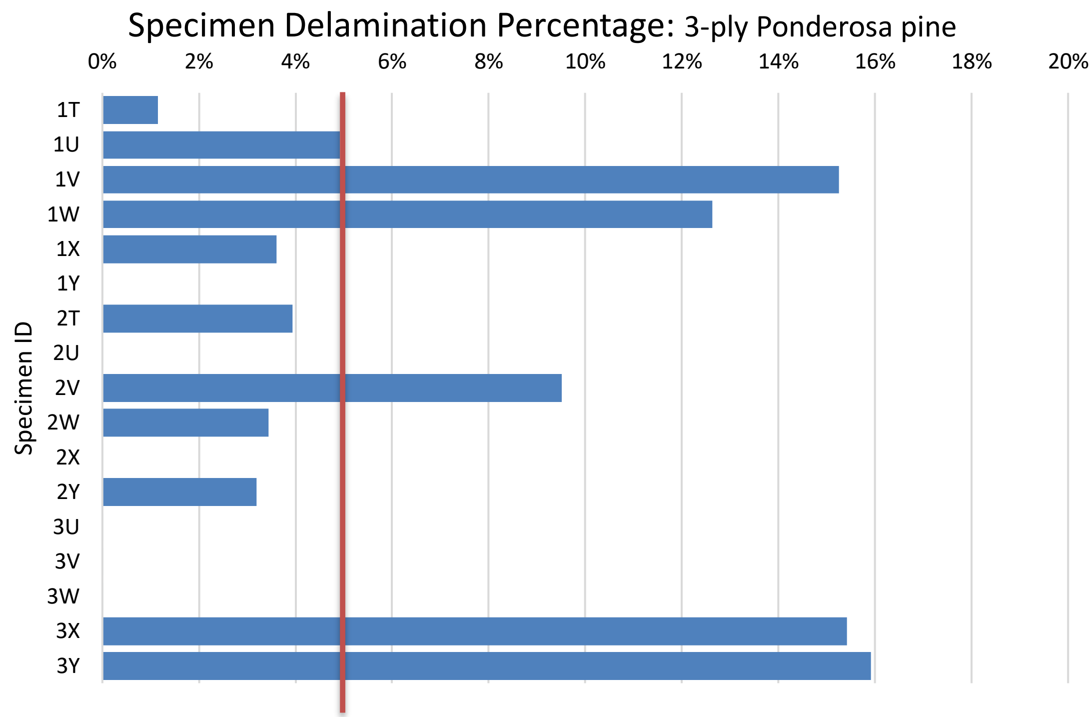


Figure 59: Individual specimen cyclic delamination results for 3-ply Ponderosa pine. The red line indicates the maximum delamination allowable.

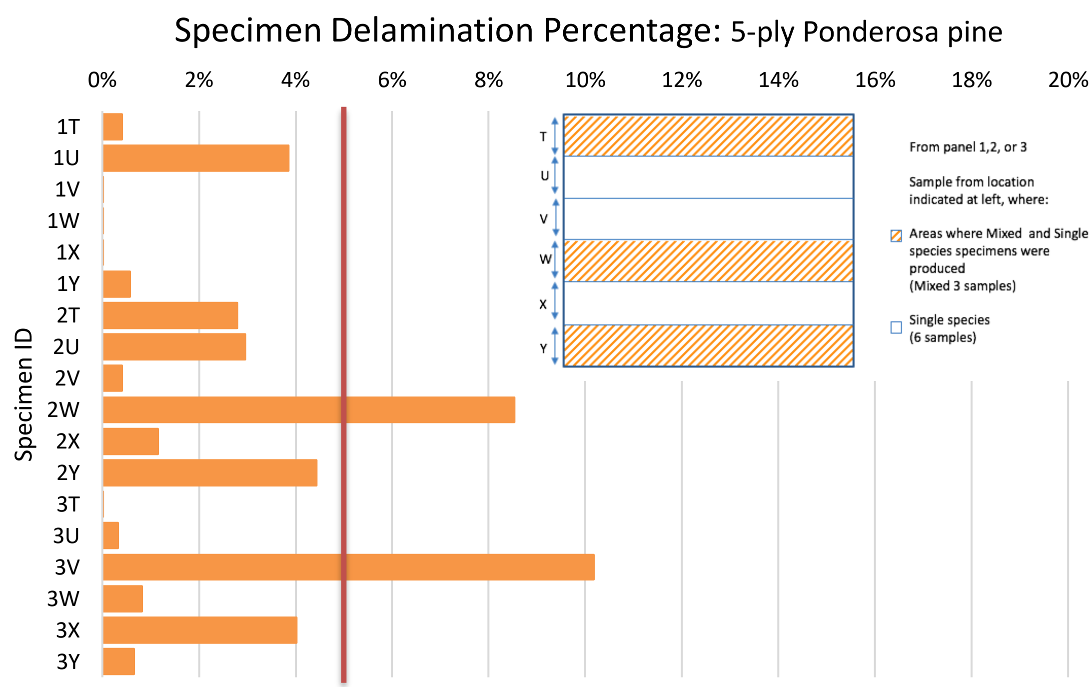


Figure 60: Individual specimen cyclic delamination results for 5-ply Ponderosa pine. The red line indicates the maximum delamination allowable.

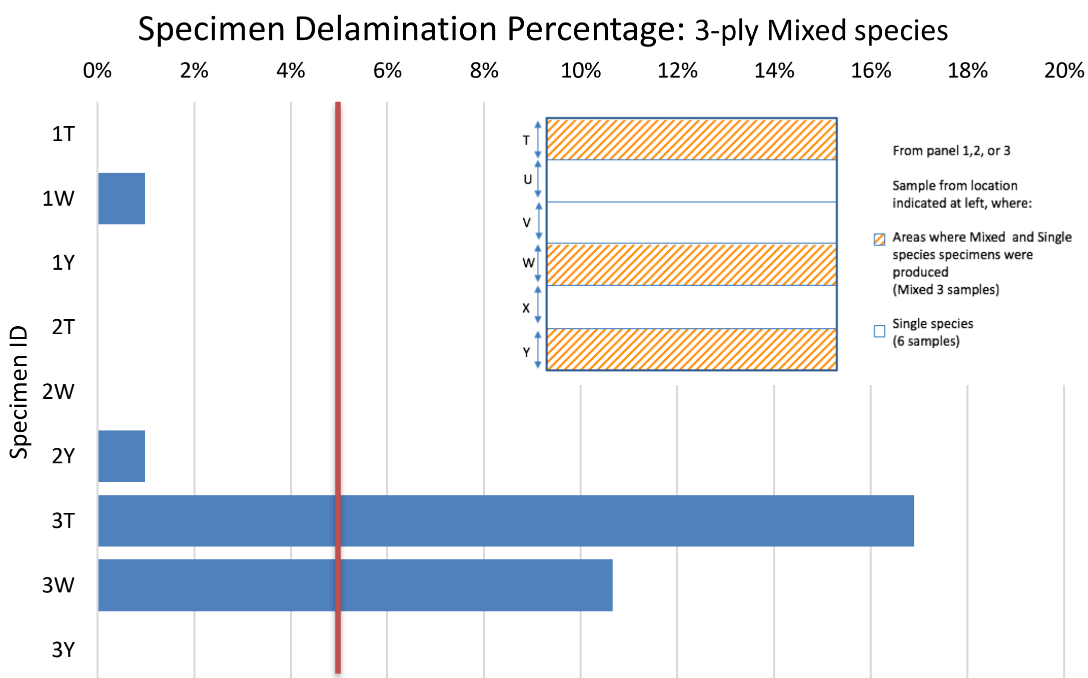


Figure 61: Individual specimen cyclic delamination results for 3-ply Mixed species. The red line indicates the maximum delamination allowable.

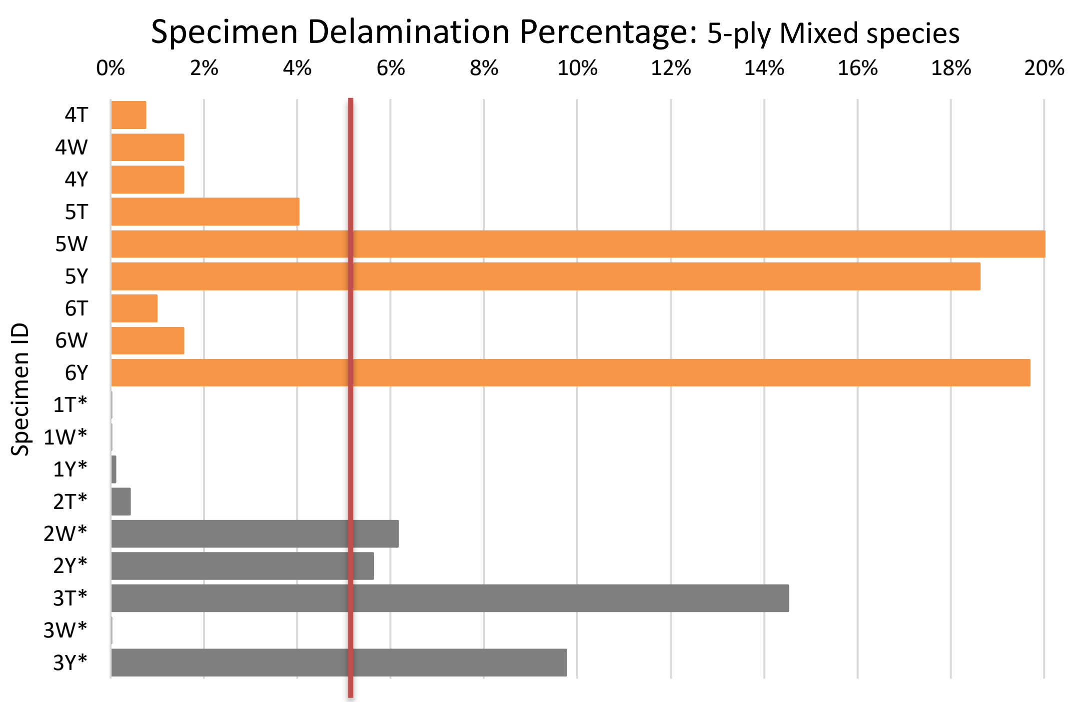


Figure 62: Individual specimen cyclic delamination results for both types of 5-ply Mixed species. The red line indicates the maximum delamination allowable. Where the "" represents samples that were homogeneously made with material thinned and processed for this project.*

3.4 Results Summary

The homogeneous 3- and 5-ply Douglas-fir control panels were the only sample groups to pass the minimum qualifications tested. 3-ply Ponderosa pine group passed the delamination criterion but failed in block shear test. All other sample groups, failed the delamination criterion, while passing criterion for block shear. All tested layups surpassed the characteristic benchmarks for f_b, E_f, and f_v.

The complete summary is in Table 9 on the next page; where “Y” represents the sample groups that met the benchmark characteristic for predefined E3 CLT grade or passed qualification criteria and “N” represents those that did not meet or pass.

Regarding the efficiency of processing the forest restoration material, although all companies selected for this project are fundamentally capable of processing small log material presently, but seem to be unprepared to handle the thinned material in an efficient manner.

*Table 9: Summary of the all the sample groups that were tested and characteristic results compared to the PRG 320-2012. Where N=Not met/Not passed and Y=Passed/Met the benchmarks and qualification criteria. * calculated as for homogeneous section (per ASTM D198).*

Panel layup		Met E3 Benchmarks (per PRG 320-2012)			Passed PRG 320-2012 Minimum Qualifications		
Ply #	Species Sample Group	f_b	E_f	f_v*	Block Shear (WF%)	Cyclic Delamination	Cyclic Delamination & Block Shear (WF%)
3-ply	Douglas-fir (Control)	--	--	Y	Y	Y	Y
	White fir	--	--	Y	Y	Y	**N**
	Ponderosa pine	--	--	Y	**N**	**N**	**N**
	Mixed core	Y	Y	Y	Y	**N**	**N**
5-ply	Douglas-fir (Control)	--	--	Y	Y	Y	Y
	White fir	--	--	Y	Y	**N**	**N**
	Ponderosa pine	--	--	Y	Y	**N**	**N**
	Mixed core	Y	Y	Y	Y	**N**	**N**
	Mixed species	Y	Y	Y	Y	**N**	**N**

CHAPTER 4: DISCUSSION

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

4.1 Quality of raw material

The material processed from the Malheur National forest resulted a surprising amount of higher grade lumber. This was not expected considering that the forest restoration operations target trees of lower value for thinning.

4.2 Primary Processing Issues

The production transportation and processing of the lumber in the facilities selected for this project was rather challenging when compared to what is typically done within the industry, where processing facilities tend to be much closer in proximity. However, this project is based on the hypothesis that the density of mills capable of processing small logs and producing CLT will increase in the region.

The difficulty of processing the material at Idaho Forest Group (Lewiston, ID) is another factor that should be considered. The production of lumber from a pulp log sort used in this project resulted in a nearly 127 minutes, or $45,000 worth of estimated downtime (Lawrence 2017); some of this downtime can be attributed to the facility not working with this harvest sort before.

Downtime highlighted the troubles that a mill could have if they were to use this small diameter material. The points in the process where most of the downtime occurred and when taken into account it may be assumed that most of the difficulties could be avoided by better sorting of the incoming logs and adjustment of the conveyer lines so that they better handle smaller logs.

The quality of the logs that were initially delivered to the mill seems to have repeatedly been the cause of downtime at the IFG mill. Since roughly only 10% of the delivered material was removed during processing, it can be suggested that a more rigorous sorting process at the point of harvesting could easily help reduce the amount of downtime and difficulty when working with the thinning material. For the logs with internal defects, such as the logs rejected before entering the HewSaw, would require internal scanning, which IFG was investigating with a new x-ray scanner on trial in their merchandizing line, but was not used to reject logs during the processing of the projects material because of the logs not being processed during regular production hours.

The point is further emphasized by Collins Co. and Vaagen Brothers Lumber Inc., which both chip the delivered logs found to be unsuitable for lumber production. Both mills, which focus on processing small-diameter logs, are set up for the highest amount of efficiency when breaking down the material from restoration programs, which means that the mills have familiarity working with these low-quality logs and potentially process the material more efficiently and cost effectively.

4.3 Panel Manufacturing

4.3.1 Efficiency and Automation

The ability to visit other CLT manufactures, in North America have led to better insight regarding further improving the production process for CLT. Automation seems to play a large role in an efficient production process.

D.R. Johnson has a more labor-intensive production line than the other three North American companies (as of 2016); this is due in-part to a non-continuous production line and manual lay-up and CLT panel handling. Structurlam, for example, uses an assisted lay-up system, with a vacuum lift, that makes it possible to efficiently layup panels and use manual labor sparingly.

Discussions with the CLT production team at D.R. Johnson indicated that they were not familiar working with the smaller widths of lumber in an efficient manner causing longer lay-up times and extra handling.

4.3.2 Screening Defects

Twisted lumber produced from the thinned material most likely contributed to loose thickness tolerances, caused by over planing. An easy remedy would be to sort out twisted pieces of lumber from production before they ever enter the CLT production line. D.R Johnson does not normally need to screen out severely twisted pieces as it is not common within the purchased lumber stock.

4.3.3 Adhesive Compatibility

It is indicated by AkzoNobel (the resin manufacturer for the MF used within the panels) that the glue spread can vary depending on wood species, wood moisture content, relative humidity in the plant, press types, assembly times, and planing quality that is used (Casco Adhesives 2009). This concept is further emphasized when the manufacturer recommends Douglas-fir being pressed at 87-116 psi, while Southern yellow pine should be pressed at 116-174 psi; a recommended general range for pressure is 43-174 psi. It should be noted that D.R. Johnson is only certified by the APA (The Engineered Wood Association) for CLT made with Douglas-fir; meaning that the company's process, and thus the resin, is specific for working with Douglas-fir. In mixed species layups and in homogeneous layups composed of species other than Douglas-fir, it is difficult to optimize adhesive formulation to work equally with multiple species. Incompatibility of the adhesive system with the species included in the mix may have contributed to the delamination failures in this study.

4.3.4 Panel Shear Properties

This test was conducted to determine the shear strength (f_v).

Though the 5-ply Douglas-fir panels were set to be a control, the sample group did not meet the characteristic set for shear strength of the prequalified E3 grade. This was interesting because the 3-ply exceeded the same benchmarks that was set by the PRG 320-2012. Further investigation is required.

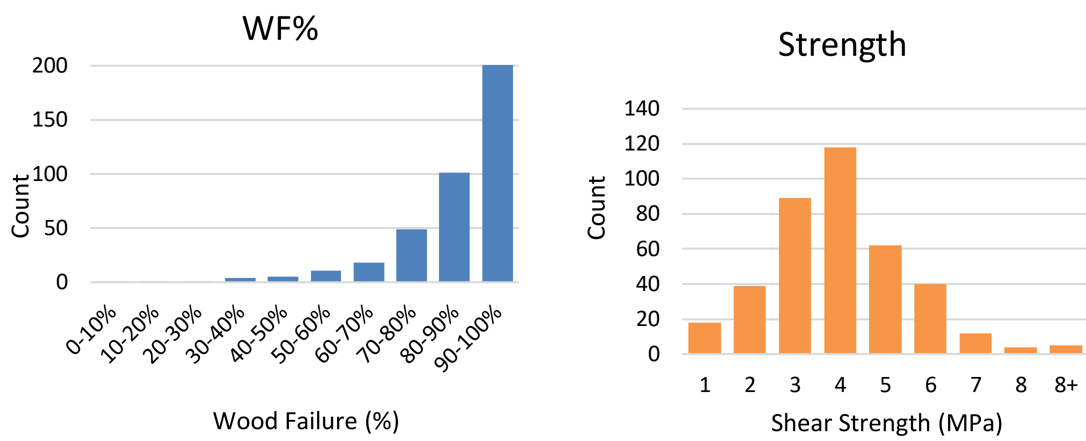
4.4 Bond Integrity

While There are many possible reasons for poor resistance to delamination of layups with forest restoration material, at this stage, we cannot definitely attribute the effect to any specific factor. However, the provenience of the test material does not seem to be a significant factor. Two leading hypotheses discussed in the following sections are focused on processing issues. This issue with delamination must be further investigated before final conclusions on the viability of the forest restoration material in production of structural CLT can be offered.

4.4.1 Shear block tests

Just as in Larkin (2017), the study did block shear testing and compared the histograms of wood failure percentage (WF%) to that of the shear strengths, showing the highly skewed results of WF% (Larkin 2017). Figure 63 shows the resulting histograms from the sample groups where it can be clearly seen that the distribution of results of the WF% is skewed to the far right, while shear strength results appear in a much more normal or bell curve shape. Highly skewed distributions of the wood failure results cannot be properly characterized by mean values or extreme values (max or min). Similarly the standard variation and COV are not proper characterizations of the distribution of this type of data.

The high COV value for 3-ply Ponderosa Pine specimen may have been caused by extended layup times of the panels and partial curing of the resin before the layup of the panel was placed in the press and pressure was applied.



(a.) (b.)

Figure 63: Histograms for wood failure percentage (a.) and shear strength (b.).

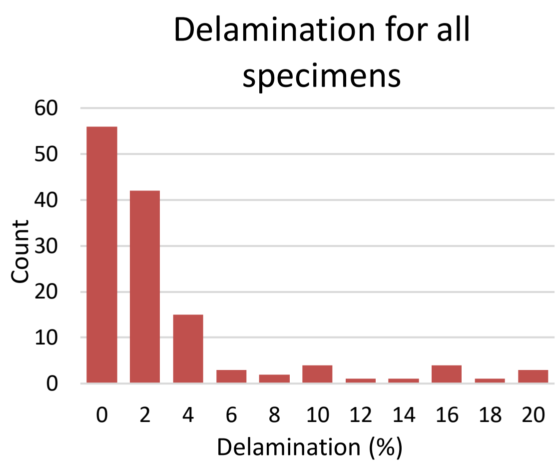


Figure 64: Histogram for delamination consisting of all specimens. No specimen failed above 20%.

4.4.2 Delamination

Most of the sample groups did not meet the cyclic delamination minimum qualification where each sample was required to have less than or equal to 5% delamination. The ones with the highest failure, in regards to minimum qualifications, were a 5-ply hybrid mixed species sample failing with 20% delamination and a 5-ply White fir, failing with 19.6% WF in block shear.

When 30 specimens were re-run through the cyclic delamination steps, due to an error in an excel spreadsheet. The effect of the second soak/dry cycle did not differ from the first soak/dry cycle more than 1% of the original value.

The cyclic delamination tests tend to be very subjective and an individual on their own must develop the skills with their samples to have an accurate understanding of what could be considered a wood failure or a delamination as a finite measurement. An experienced cyclic delamination researcher from the APA has checked the procedures used with the specimens and found no inconsistences with what was done to how the specimens would have been qualified at APA (Jennings 2017). With many samples, there is limited depth perception that occurs with the test specimens, which allows for no understanding of how large a failure area can be.

The corners of the specimens where two pieces (Figure 65) of lumber met with unbonded narrow edges were initially a concern, but no excessive amount of failure at those locations was found.

Figure 65: Cyclic delamination sample showing un-bonded edges that caused very little to no delamination on the bonded faces.

There were specimens that clearly failed in delamination, as seen in Figure 66. While there are many possible reasons for poor resistance to delamination of layups with forest restoration material, currently we cannot definitely attribute the affect to any specific factor. However, the provenience of the test material does not seem to be a significant factor. Two leading hypotheses discussed in the following sections are focused on processing issues.

Causes of failure for these specimens could have been due to: lumber being planed too thin causing inconsistent pressure, allowing the adhesive to cure but no bond to be formed. Another possible reason may be the incompatibility with the adhesive system formulated for Douglas-fir used in the test with other species. Incompatibility of the adhesive system with the species included in the mix may have contributed to the delamination failures in this study as well.

Further investigation would be required to verify these hypotheses. Other studies also reported excessive delamination of hybrid panel lay-ups (Hindman and Bouldin 2015; Larkin 2017).

Figure 66: A mixed species sample that resulted in high delamination.

4.5 Discussion of Future Work:

The next step would be to: perform an in-depth investigation into the causes for delamination and ways to reduce or eliminate failures to potentially qualify the material for the PRG 320-2012. In particular, the effect of thickness tolerances that result from processing severely twisted laminations needs to be determined and the effects of potential incompatibility of the adhesive system when using mixed species within a layup.

CHAPTER 5: CONCLUSION

The general goal of this project was to determine the technical, or mechanical, viability of utilizing small diameter (small-end diameter of 3.5”- 6”) logs within structural CLT products. Specific objectives were to:

(1) Determine if CLT panels utilizing low-value lumber from forest restoration operations in core layers of laminations meet PRG 320-2012 product qualification criteria;

(2) based on findings of Objective 1, propose respective changes to the current North American product standard PRG 320-2012 to allow low-grade forest restoration material in structural CLT products;

(3) Investigate the impact of small logs from forest restoration programs on the efficiency of the primary and secondary processing.

The conclusions of this study will be presented in the context of its objectives.

5.1 Objective 1

Overall, 21 homogeneous and hybrid CLT panels utilizing lumber from low-value logs generated in forest restoration operations in core layers were built and tested against the engineering benchmarks and qualification criteria for structural CLT panels per the PRG 320-2012. The mechanical characteristics of 3-ply and 5-ply Mixed species CLT panels met the E3 benchmark for f_b , E_o, and shear resistance criteria for percentage of allowable wood failure. Of the 21 3- and 5-ply CLT combinations incorporating homogenous and mixed specie layups, only the reference layup, 3 and 5-ply Douglas-fir, passed the minimum qualifications of the PRG 320-2012 in terms of delamination and wood failure, criteria.

The cyclic delamination test resulted in failure for both the 3- and 5-ply Mixed species panels, which consisted of No. 2 visual grade on the exterior and small-diameter material in the interior.

Although no definite correlations can be offered at this point, cyclic delamination failures can be potentially attributed to problems that occurred within the manufacturing process. Two specific hypotheses were offered: (1) incompatibility between the adhesive system at D.R. Johnson, where it is optimized for Douglas-fir and not specifically for the other species used within the study; and (2) loose thickness tolerances that resulted from processing of severely twisted prices of lumber.

5.2 Objective 2

With the negative outcome of the technical validation of hybrid layups, including material for forest restoration treatments, the results warrant no changes in the PRG 320-2012 to accommodate hybrid layups with low-grade/low-value material removed from the Blue Mountain and Fremont-Winema regions.

5.3 Objective 3

One of the findings of this project was that processing the thinned material was a challenge. A significant number of logs deemed unsuitable for processing had to be removed before merchandizing at the sawmill began. Characteristics such as rot and animal damage are more common in trees targeted for removal in thinning operations than would have occurred if the same area was harvested for profit. These characteristics lead to processing difficulties during material breakdown at the mill. Despite the line being nominally capable of processing logs down to 3.5 inches on the small end, downtime and delays were experienced at the sawmill mostly due to unfamiliarity with processing the small logs. Downtime could easily be reduced by culling unsuitable timber when harvesters are sorting/on-site processing at the treatment site in the forest.

The current level of automation of processing techniques used within the North American CLT industry varies. While some companies are highly automated (i.e. Nordic Structures), D.R. Johnson still relies on manual labor. The company could benefit from the addition of automated steps during their production process.

5.4 Future work

The future work should focus on the verification of the hypotheses regarding the causes for delamination and ways to reduce or eliminate the failures: (1) determine the effect of loose thickness tolerances resulting from processing severely twisted laminations; (2) separate and determine the effect of potential incompatibility of the adhesive system used with mixed specie layups.

It may still be possible to use the lumber within crane mats, or non-structural grade CLT; currently, there are no crane mate standards to be met. Other secondary wood products may also be an option.

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APPENDIX

List of Appendices

APPENDIX A: Trip Reports

A1: Iron Triangle Field Report

Christina Lawrence

The goal of this trip was to understand the harvesting process of the collaborating company, Iron Triangle.

Attendees: Christina Lawrence and Brent Lawrence

Host: Iron Triangle; Zach Williams

What is standard for harvesting on lands owed by the USDA is the prescriptions and the standards for forest practices, which are held to higher restrictions. Since the timber that comes off the lands is mainly low grade, the material is typically chipped or placed into a burn pile and covered until the next spring or fall. Another option for the waste, is to chip it and then redistribute it within the surrounding forest to help with fire fuel management.

Some of the factors that affect the outcome of the species that grow within an area are elevation, precipitation, slope of the area, and among other environmental factors. The patch that was harvested for our material was slightly sloped and resulted in the majority of our harvested material as Ponderosa pine, White fir and a minimal amount of Douglas-fir.

Timber harvesting for the USDA is a relatively simple process that consists of the following:

1. Winning the stewardship contract
2. Marking of timber according to forest plan
3. Cut-to-length of timber
4. Forwarded/ loaded onto truck
5. Transported

6. Chip what could not be sold as timber

What was done differently for our project compared to that of a standard harvesting practice was relatively minor. The sorting process was much more relaxed to better reflect what material comes out from the harvesting/thinning area in the center of the Malheur National Forest. Particularly small-diameter material is traditionally chipped for burning, but was included in the material that was placed on the trucks and sent to Lewiston, ID for processing.

Figure 67: Harvesting sight in the Malheur forest.

This lack of sorting may have been the cause of so much material being removed during the sorting that occurred at the Idaho Forest Group (IFG) mill. Throughout the process flow, and after the sorting done by IFG, a significant amount of timber was unable to be processed by their HewSaw and a few pieces were removed further down the line at D.R. Johnson’s facility.

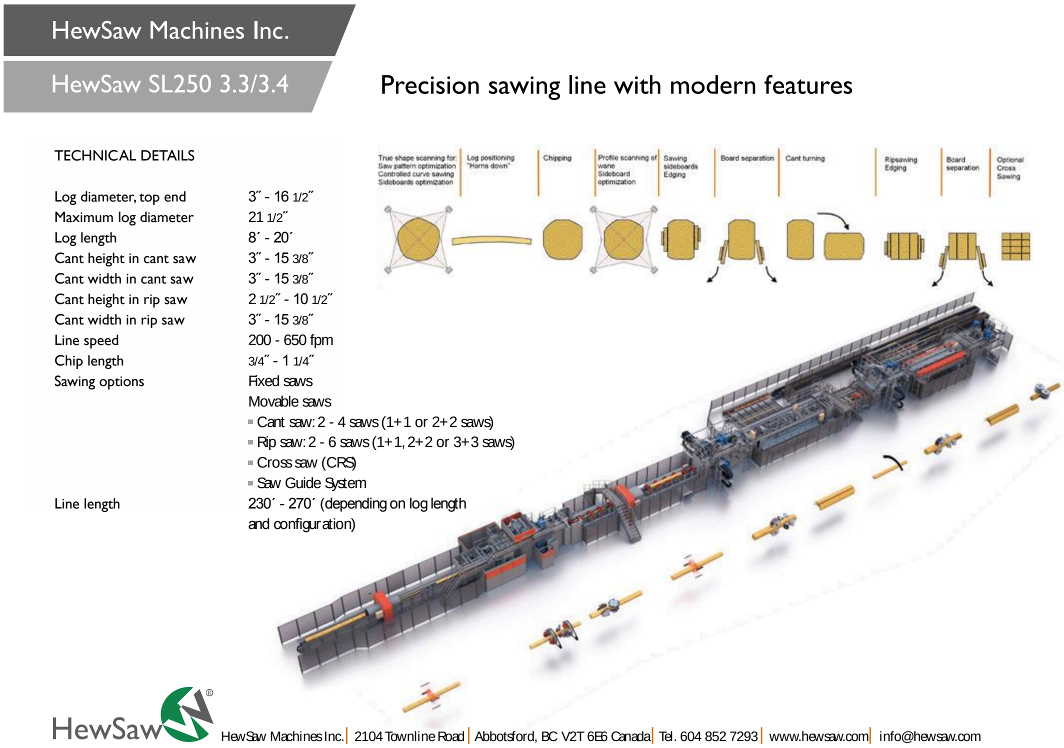
A.2: Idaho Forest Group Lewiston Mill Tour and Log Processing 1/23/0216

By: Christina Lawrence

Our group's trip that included Lech Muszynski, Chris Knowles, Brent Lawrence and Christina Lawrence was for the purpose of seeing Idaho Forest Group's Lewiston mill process the lumber that will be used for the core of our cross laminated timber panels. Being able to see the breakdown of the logs was a great benefit for our research because of the need to understand the difficulties that a mill might come across when dealing with our unique timber.

The benefits that this particular mill has over other are the addition of some new scanners and the mill's new HewSaw. The HewSaw SL250 3.3 (Figure 68) provides a great advantage for this company because of its quick processing time and the ability it has to cut down to a roughly 4.5" small-end diameter log. Before the timber can be processed, the logs go through extensive scanning and re-scanning before being sent through the HewSaw. The logs are currently being initially scanned by CT.log scanner produced by Microtech (Figure 69). This scanner allows for the logs to have a 3-D image produced, and from those, estimations can be made about the quality or where potential defects may lay in the wood.

Figure 68:HewSaw process. (http://www.hewsaw.com/na/products/hewsaw-sl250-3-3)



Some of the other benefits that this particular mill has is how they organize their timber. The IFG Lewiston mill groups their timber during the merching process (Figure 66). This method allows them to work more efficiently in the long run, where the saw blades in the final process have to move less in order to accommodate the timbers lengths. As a result, the mill can save time, which results in saving money,

Figure 69: CT. scanner

produce more lumber, and can potentially produce higher quality lumber. During this process, they also orient and make the logs symmetrical, shaving off material on the larger end of the log for best results.

To ensure that the timber is cut the most beneficial way, throughout the merching process logs are continuously scanned with MPM scanners and sent through metal detectors. The metal detectors are an important aspect of the process in mills because they ensure that no metal is stuck within a log, which could potentially destroy an expensive saw blade—this would result in downtime for the mill and damage for the blade. The MPM scanners do something similar to that of the Microtech CT.Log scanner in determining what the quality of a log might be and what defect it may contain.

The sawmill also has a Nicholson high-speed debarker A8 hyd, which they claim is one of the fastest debarkers in the world.

Figure 70: The presorting process at IFG.

The timber that was used for this trip was previously sent to the mill by Iron Triangle out of John Day, OR who initially harvested the material. The loads of timber were sent to the mill, where roughly 20% was immediately rejected for use due to rot, too much curve, insect damage, etc. As the mill continued to process the remaining timber, after the merching, some additional timer was removed. This material made it through the debarking; however, when it reached the HewSaw some were difficult to run through and needed to be removed. Similar to what was initially removed from the harvest that was delivered, some additional timber was found to have rot, excessive curvature, and the diameter was too small for the saw.

Figure 72 Log defects causing them to be removed.

Figure 71: Animal defects of removed timber.

The above figures show some of the defects the rejected timber contained. Other features included rot and significant curvature in the log, making it impossible to send through the HewSaw.

A.3: D.R. Johnson Field Reports

A.3.1Pre-Panel Visit
Jan.22-23,2016

By: Christina Lawrence

The goal of this trip was to understand why D.R. Johnson wanted to take on the production of Cross Laminated Timber and to observe their production process.

Attendees: Christina Lawrence and Brent Lawrence

Host: D.R. Johnson; John Redfield

The purpose of this trip was to obtain some initial information on the process of production for Cross Laminated Timber (CLT) and how D.R. Johnson produces this product. The company will put the final added value product together for the small diameter timber that will be delivered from the USDA forestland. Because of the recent introduction of CLT to the company's production line, they have a minimal amount of space to produce their panels, in terms of numbers and size. The company is currently producing panels that are 10 feet wide and 24 feet long (note date of report), but there is a demand for panels ranging upwards to 40 feet; the company did not reveal any adjustments to the production line currently to accommodate this demand.

In order to create their panels the company is currently using Douglas-fir lumber that is derived from 35 to 40-year-old trees and processed in a nearby mill. The material meets the needs of the company since it is square-edged and has 12% +/- 3% moisture content. This is an aspect of the research project that's being considered because of the age and size of the trees may result in have significant changes to the mechanical properties of the panels. The employees working in this branch of the company have a good understanding of needs with an average of 30 years of working in the industry. The newest employees for this production line work on the Computer Aided Design program, or CAD, and have been a part of the company for less than a year.

The overall production line of CLT is relatively basic and not all that complicated. Lumber is taken in, replaned/planed, finger-jointed, glued together via the finger-joints, a panel is laid up, the companies two-part melamine resin spread on top (each panel uses about 60 lbs.), the last two steps being repeated until 3, 5, or 7 layers are achieved, then the panel is ready to be pressed. Where pressure is applied to three of the panel's sides to ensure no gaps are left. D.R. Johnson had a customized pneumatic press built by USNR. The press time, is dictated by the temperature and humidity of the production day, which can cause it to range between 2-4 hours. The press puts a pressure of 120 psi on the panels. In total, a board can be physically moved by an individual upwards of 6 to 7 times, which seems rather high given that the production of lumber could be moved 1 to 2 times by an individual throughout the timber breakdown process.

Figure 73: Finishing equipment for CLT panels at D.R. Johnson.

One of the limiting factors that the company currently has with their production line is the final step in the process—finishing touches. This refers to all the door frames, window frames, and any other additional feature that needs to be

Figure 74: D.R. Johnson used a chainsaw to make the needed cuts on the panels.

done in order for maximum efficiency when putting the building together. They are currently using hand tools, such as the ones that can be seen in Figure 73 and Figure 74. Due to the use of these machines, it causes the company to have a limited amount of space as to where they can layout the panels in order to finish them—in Figure 71 you can see that the "CLT area" can only comfortably fit 4 to 5 panels.

Figure 75: The custom press produced by USNR.

However, there are some things that are being done in order to increase the capacity of the company's CLT line. They have already ordered and are in the process of getting a Computer Numerical Controlled (CNC) machine that will be around 10 ft x 70 ft, allowing the company to be much more efficient and accurate in final stages of production. This addition to the production line should be completed sometime in the 1st quarter of 2016. Along with the new CNC machine, the company is also looking to build additional storage/work space to accommodate the panels.

Besides some of the before mentioned challenges that the company is facing, there is also that of the demands of the customers. While CLT is meant to be a low-cost alternative in construction materials, many customers are wanting clear/high grade lumber on one or both faces of the panel. Some of the other challenges that have arisen with this product is the market education. There are currently only about four companies in the entire North America that are producing CLT, which means that there is a large amount of market education and outreach that needs to be done before the product can be easily and fully accepted into the construction segment. D.R. Johnson says that they are in committed to this product for the long term. Since its debut as a product, standards have been created to better accommodate the new paneling. One example of a project that D.R. Johnson worked on was a new building at Western Oregon University. The installation of CLT greatly helps with decreasing the cost of construction because of the prefabrication, the quick construction, and in a way the decreased installation needed for the building.

Figure 76: Closeup of the press closing.

D.R. Johnson has an advantage over many other companies that are looking to put in a CLT production line. This advantage is because the company is already producing a Glue-laminated timber, which means that the company previously purchased a finger-jointer, a planer, and had the supply of high quality lumber needed for CLT production. While the company was unwilling to tell us how much they have spent to put in the new production line, they did estimate that if they did not previously have any equipment and were to start the production line from scratch it would cost the company between $30-40 million. The company is hoping that other mills would be willing to make this investment to help develop the market education and help expand the need for the product.

One of the more difficult aspects of this product is the transportation. Because of the prefabrication it is essential that the quality of the exterior surfaces is maintained. Much of the time the CLT is transported via truck; however, the company has been working on a project in New York which would most likely require transportation via railway. This also is a slight problem when it comes to working with the architects/engineers/designers in that they are not well educated in what they abilities of what not only CLT and wood products as a whole.

Overall, the new CLT production line has added eight more positions to the company, which in-total employs around 40 people. The addition of CLT to the production line has produced about a 15% increase in workload to the two finger jointing shifts, which is covered by 5-10 workers. There has also been an increase for the CAD workers at the company, where roughly 25% of their time has been shifted to CLT designing.

Some of the inhibiting factors that D.R. Johnson has found from adopting the CLT presses were:

- Cash flow
- Time because the company had been trying to build around what the company currently has and making the CLT production seamless

This was a very insightful trip to make and to be sure that those conducting the research have a better understanding of the final process that the CLT panels will take. We felt that D.R. Johnson had a good understanding and good start for the U.S. market on CLT.

Conclusion:

This trip better allowed us to understand the process by which CLT is produced and the sort of barriers that may develop with this industry. Having very few facilities within North America, it was important to see a start of production here comparable to those that are in Austria. This will also be the company that will producing the panels for our project with the USDA. With the visit, we were able to better understand any restrictions or points that may later need trouble shooting for the production. Market was another point of discussion that made it easier to understand where demand is and might be.

DR Johnson Panel production process Visit

6/1-2, 6/9/2016

Christina Lawrence

The purpose of this trip to supervise to production of the project's CLT panels and the samples at D.R. Johnson's (DRJ) facility.

The production process required multiple trips due to the company being behind in production, mainly on the finger jointer, because of the addition of a Hundegger PBA CNC machine to their process. Upon arrival at the company's facility, some of the panels were already pressed and waiting on the Hundegger PBA racks for the breakdown of the panels into samples. There seems to have been some lack of communication which caused the panels to be produced entirely of USDA material, where the original plan was to have the panels have United States Department of Agriculture (USDA) material cores and DRJ exterior layers. However, there was not enough Douglas-fir USDA material for more than one full panel, so there was a large amount of DRJ material that was cut down to the 2x4 size that our panels used to supplement the Douglas-fir. DRJ usually uses 2x8s. The mixed species panels did have the cut-down 2x4 DRJ material on the outside of those panels.

The single species panels were not ideally cut for testing, but were produced as would be industry standard. This means that while it was requested to have 3- and 5-layer single species panels, DRJ produced two 7'x18.7' panels (one 3-layer and one 5-layer) and then produced a cutting pattern on the Hundegger PBA with three of the 6'x6' cut pattern. The cut pattern can be seen below and an example of how the two panels were broken down can be seen below.

The cut pattern that was requested for the panels, as stated by program operator, "was one of the most challenging ones they have used so far". This of course being roughly the first week of them using the CNC machine. However, the challenge of the pattern requested was because of the small and precise measurements that needed to be done for the smaller samples needed.

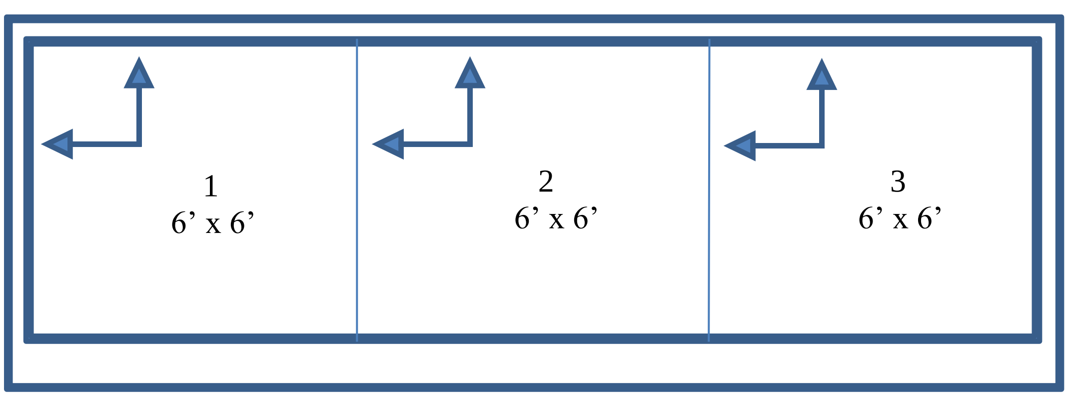


Figure 77: Cut pattern of the three combined smaller panels that were later broken-down in the CNC.

As mentioned, DRJ typically uses 2x8s when making CLT panels, not 2x4 s and this is because of the amount of handling that involves smaller pieces of lumber. A panel takes more material and time to create, which changed the time frame of a standard layup. The lumber was dried between 9% and 12% moisture content. D.R. Johnson does their best to source their lumber from local mills, their sources being mainly consisting of:

- Frank Lumber Co. (Mill City, OR)
- Bennett Lumber Products (Princeton, ID)
- Others (looking into Superior Lumber in Springfield, OR)

The newest addition to DR Johnson's production line is a Hundegger PBA CNC machine. This allowed the company to cut our material, using a cut pattern that we sent them, in a fraction of the time it would have previously taken. Given that the machine had only been set up at the company for about a week, there was a learning curve when developing the programing for the CNC. One example, was to make sure that the design was set for the correct corner that after pressing ended up squared (Figure 78). One end of the panels had to be screwed down to minimize any movement that may have occurred during the cutting process, particularly with some of the smaller cuts that needed to be made. This did cause a bit of a risk with the possibility of hitting of these screws, but, thankfully, no damaged occurred during the cutting. Some of the features that DR Johnson's new Hundegger PBA came with were a circular saw that was roughly 1000cm wide and an 8 in. diameter chainsaw (of which replacements could cost upwards of $2,000), both of these were on a five-axis rotary system. One benefit that the company has, is that their CLT line supervisor has been working for the company since their qualification roughly 1 and a half years ago.

To ensure that panels are square for cutting (for our project) they were made somewhat larger than requested in order for them to cut out the center of the panels and ensure that each corner was perfectly square. They did start out with a squared corner, this can be seen below, which ensured that the Hundegger PBA cuts were as square as possible.

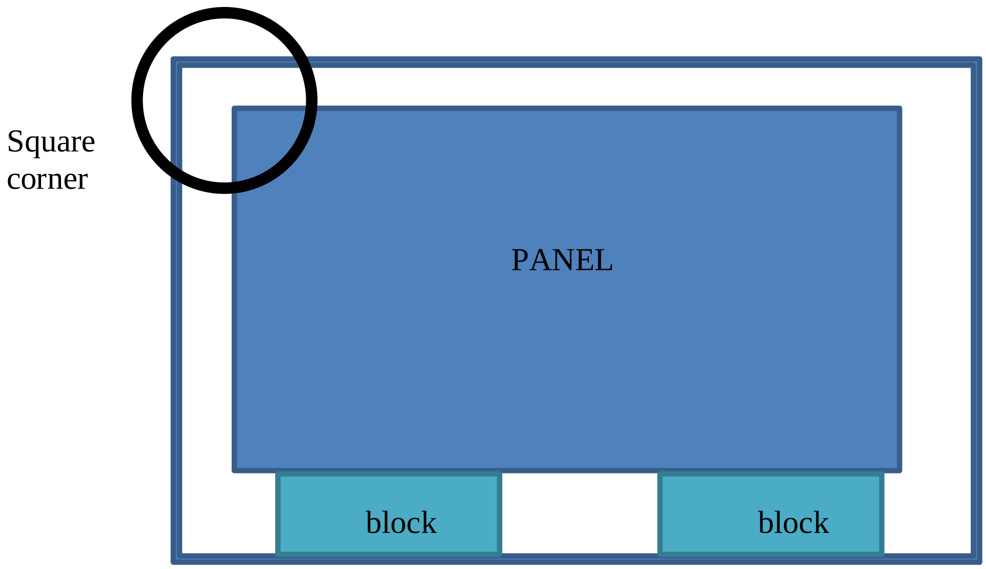


Figure 78: Outline of how the interior press was set up.

With all the changes that needed to be made to accommodate the USDA material, there were not significant changes made to the length of time that was needed to press the panels—or rather there was no evidence that the press time needed to be adjusted. Each panel did not take a significant amount of time, which ranged from 30 min. (for a three-layer panel) to around 45 min. (for a five-layer panel). The company stated that it would have taken them a full eight-hour day to cut each panel into the requested cut pattern.

The adhesive application is what would be expected, with the layup being passed under the drip lines of the resin and hardener about 4 to 5 times, depending on the size of the panel. The separation of the resin and hardener ensures that the CLT team has the maximum time to layup the entire panel and place it into the press for the best results. It also allows the resin-to-hardener ratio to be adjusted according to the temperature of the air and lumber. Despite the adjustment that can be made with the ratio of resin to hardener, this does not affect the amount of time that D.R. Johnson presses their panels. The company still places pressure on the panels for roughly two hours; meaning, that the maximize production rate to 4 panels per day, depending on the number of layers the panels have. Two panels can be made at once when pressing 3-ply; there is enough room in the press to stack the panels on top of each other. The ideal temperature for production is 70 F degrees. While it is possible to setup a panel at higher temperature, this temperature allows for the resin and hardener to react at a more controlled rate. It takes a mere 30 minutes to lay up a panel. This means that the entire production time for a panel can range from 3 hours and 30 minutes to 4 hours—from layup to wrapping.

The process of panel pressing is relatively simple. The steps for pressing are as follows:

1. Panel is inserted into the press and pressure is applied on that face.
2. The side pressure is then applied
3. Finally, the top pressure to ensure that the panels is flat is applied.
4. The blocks are used to adjust the size of the press to accommodate the requested panel size.

One of the problems that occurred with our lumber was warping. There were some boards that had so much warping occurring that it was difficult for the CLT linemen to get the laid-up panel into the press; it caused them to have to use a scrap board to press the ends of the panel down for it to fit into the press.

Since our initial trip to D.R. Johnson's facility, they continue to lay-up the panels by hand, but they do have a machine or two in the works for optimization of panel production. However, it is not always the best to have a completely mechanical production process when it comes to CLT; when done by hand, the linemen can ensure that each board has maximum glue exposure and remove any debris that may have made its way into the layup. This last benefit is particularly important because the facility is still under construction from its addition of the Hundegger PBA and additional storage area.

With the White-fir 5-layer panel, in particular, the press had problems with tip pressure causing it to have pressure only on the side for a short time.
Some of the material had to be thrown out due to the inability to finger joint; this was half dozen pieces because of rot.

After the completion of all the panels produced with the thinned material, D,R, Johnson provided us with the information that was gathered during the production process and for the individual panels.

Panel Production specification sheets:

Date 5-30-16

Process check #4 CLT

Lumber Planning

panel #	#	#	#	#	#
Lumber size	2x8				
Thickness	1.375				
Across Width	.005				
Down Length	.008				
Moisture Content	9 - 12%				
Bond surface	good				
Grade major	std				
Grade minor	std				
Appearance	Ind				
Date and Time Planned	5-31-16				
Checked By					

Comments

Glue Spread Rate AITC Test #102 88# By RB

Pressing x2 panels ~1 hr. Small wood (2-3ply)

panel #	#050 test		#		#		#		#	
	Start	Closed	Start	Closed	Start	Closed	Start	Closed	Start	Closed
Assembly Time	1:39	2:35								
Air Temp	80°									
Lumber Temp	77°									
Mix Ratio	40/100		/100		/100		/100		/100	
Glue spread	85#									
Press (psi)	105									
Size lumber	2x4									
Panel size (LxW)	7x18									
	WF + Pine		L3							
Ran out by	RB									

3panelsx2

Riddle Laminators Mill # 1117 Form: Process-control #4 June / 2015

Quality Assurance [signature]

Date 06-1-16

Process check #4 CLT

Lumber Planning

panel #	#	#	#	#	#
Lumber size	2x8				
Thickness	1.375				
Across Width	.005				
Down Length	.008				
Moisture Content	9-12%				
Bond surface	good				
Grade major	std				
Grade minor	std				
Appearance	Ind				
Date and Time Planned	5-31-16				
Checked By	RB				

Comments

Glue Spread Rate AITC Test #102 85# / 97# By RB / RB

Pressing

44 small wood   48 5ply

panel #	# OSU test		# test		#		#		#	
	Start	Closed	Start	Closed	Start	Closed	Start	Closed	Start	Closed
Assembly Time	9:06	9:50	1:10	1:50						
Air Temp	61°		80°							
Lumber Temp	66°		83°							
Mix Ratio	70 /100		30 /100		/100		/100		/100	
Glue spread	82#		92							
Press (psi)	105		105							
Size lumber	2x8		2x8							
Panel size (LxW)	7x18		7-18							
	Pine LS		WF LS							
Ran out by	RB		RB							

3 panels   3 panels

Riddle Laminators Mill # 1117   Form: Process control #4   June / 2015

Quality Assurance [signature]

Date 6-7-16

Process check #4 CLT

Lumber Planning

panel #	#	#	#	#	#
Lumber size	2x4				
Thickness	1.375				
Across Width	.004				
Down Length	.008				
Moisture Content	9-13%				
Bond surface	good				
Grade major	std				
Grade minor	std				
Appearance	Ind				
Date and Time Planned	6-7-16				
Checked By	RB				

Comments

Glue Spread Rate AITC Test #102 85#/99# By RB / RB

3 panels 45 38

Pressing L5 054 L5 054

panel #	# Douglas Fir		# Mix		#		#		#	
	Start	Closed	Start	Closed	Start	Closed	Start	Closed	Start	Closed
Assembly Time	8:45	9:30	1:10	1:48						
Air Temp	73		87							
Lumber Temp	72		88							
Mix Ratio	80/100		40/100.		/100		/100		/100	
Glue spread	85		100							
Press (psi)	105		105							
Size lumber	2x4		2x6							
Panel size (LxW)	7x18		8x18							
Ran out by										

Riddle Laminators Mill # 1117 Form: Process control #4 June / 2015

Quality Assurance [signature]

Date 6-8-16 Process check #4 CLT

Lumber Planning

panel #	#	#	#	#	#
Lumber size	2x4 - 2X6				
Thickness	1.375				
Across Width	,004				
Down Length	,008				
Moisture Content	9-13%				
Bond surface	~~[illegible]~~ Good				
Grade major	Std				
Grade minor	~~[illegible]~~ Std				
Appearance	Ind				
Date and Time Planned	6-7-16				
Checked By	RB				

Comments

Glue Spread Rate AITC Test #102 77# / 79 / 67# By RB/RB/RB

Pressing

panel #	# MIX L5 (230 min. OSU)		# MIX L5 (45 min. OSU)		# MIX L3 (42 min. OSU)		#		#	
	Start	Closed	Start	Closed	Start	Closed	Start	Closed	Start	Closed
Assembly Time	6:48	7:26	10:15	11:00	2:18	3:00				
Air Temp	66°		70°		70					
Lumber Temp	71°		71°		70					
Mix Ratio	80/100		80/100		~~/100~~ 50/[illegible]		/100		/100	
Glue spread	80#		80		~~80~~ 65					
Press (psi)	108#		105		105					
Size lumber	2x4 - 2x6		2x4 - 2x6		2x4					
Panel size (LxW)	8X18		8X18		8X24					
Ran out by										

Riddle Laminators Mill # 1117 Form: Process control #4 June / 2015

Quality Assurance [signature]

/Spread rate : 73-100
/Lum. temp. : 63-88°
/MC : 9-13%
/Press (psi): 105

Date 6-9-16

Process check #4 CLT / lay-up : 20-45 min.

Lumber Planning

panel #	# 2x4 -2x6	#	#	#	#
Lumber size	.1375				
Thickness	1004				
Across Width	1008				
Down Length	↓				
Moisture Content	9x13%				
Bond surface	good				
Grade major	Std.				
Grade minor	Std.				
Appearance	Ind				
Date and Time Planned	6-7-16				
Checked By	RB				

Comments

Glue Spread Rate AITC Test #102 75# / 71# By RB / RB

Pressing

21 min. OSU ≈ 20 min

panel #	# 2x4 DF		# 2x4 mix		#		#		#	
	Start	Closed	Start	Closed	Start	Closed	Start	Closed	Start	Closed
Assembly Time	7:40	8:01	1:08	1:26						
Air Temp	61°		78°							
Lumber Temp	63°		74°							
Mix Ratio	100/100		70 /100		/100		/100		/100	
Glue spread	75		73							
Press (psi)	105		105							
Size lumber	2x4		2x4							
Panel size (LxW)	8x18		8x12							
	L3?		L3?							
Ran out by	RB									

Riddle Laminators Mill # 1117 Form: Process control #4 June / 2015

Quality Assurance Randy Burke

A.4: Structurlam, Smartlam, Vaagen Brothers and Structurecraft

Structurlam:

We were given a tour of this facility, located in Penticton, British Columbia, Canada, by Ron McDougall. They have been producing CLT for roughly five years. In the first two and a half years they received government backing, but commercial popularity has expanded over the last few years.

Similar to D.R. Johnson, Structurlam typically uses 2x6s for their panels; however, they also use 1x6s for particular panels. As might be expected, the 1x material is only used in the weaker direction due to its weaker strength properties. They were unsure what their drying times were due to the wide range of moisture content they tend to receive. One unique aspect of Structurlam, is how they achieve the required 12 +/- 3% MC. They do this by buying material at upwards of 19% and then air drying to the recommended moisture content. They receive their material from roughly six difference sources. What lumber comes to the company is what they use, this means that the company uses blue stained material that is shipped to them and still meets grade. They also use material with a small amount of wane. The company is able to layup a panel of 10 x 40 ft in roughly twenty minutes, which then goes through a 45 to 50-minute press time with a vacuum press and a two-part melamine for their panel production. Structrlam also has a Hundegger PBA.

The company takes pride in what they do. Every panel is tested for cyclic delamination and if any is found the production line is shut down until the problem can be determined and fixed. This technique helps the company ensure the best quality of panels and that they continue to meet standards, which is particularly important due to the American and Canadian standards being equivalent. Another quality factor is that the company uses humidifiers in the shop and work areas to help the lumber stay at the preferred moisture content.

Smartlam:

This company is located in the small community of Columbia Falls, Montana and the tour was given by Robert Tudhope, the VP of Product Development. Being five years old, the company has multiple backers that are helping to further expand the company and soon they will have their own production site—currently they are leasing a warehouse from an investor. The use of investors, with little to no funding from Montana, is unique for North American CLT companies, who typically receive funding from government grants.

The company is currently looking for another site to expand into, but plans to stay in the Montana area. Sites that are being looked at are an old Weyerhaeuser mill and a 20-acre site. The expansion of space is not only useful for production, but also Smartlam is working with the APA to develop a more local PRG 320-2012 laboratory. One of the company's investors, Western Building Center, provides all the companies connection pieces.

Robert was able to give us some information on some of the new products that the company is developing and, while for confidentiality reasons they cannot be discussed in detail, the products that the company is expanding on will go a long way in helping CLT become more mainstream.

Vaagen Brothers:

The Vaagen Brothers mill in Colville, WA has a unique collaboration that many others do not. These collaborations allow the mill to be able to run small diameter material for USDA lands and still make a profit. With the nearby mill that takes Ponderosa pine, a biomass facility and the additional two other Vaagen brother mills (an additional stud mill and one located in Canada) it is clear to see the unique situation that the company has been provided and become an overall success.

We can make the assumption that the composition of what is taken to Vaagen brothers from USDA lands is similar to what was pulled (in order of largest to smallest ratio: Ponderosa Pine, White fir, and Douglas-fir). While the mill does not take Ponderosa Pine, this goes to a nearby mill, there are still an estimated 300 trucks that pass through mill property a day. Only 100 are needed to sustain mill operation per day. Because their material comes mainly from federal lands, and with the terrible fires that been occurring over the last few years, the company has been and still is currently taking burn material.

Little sorting is done at the harvesting site and is mainly accomplished at the mill for efficiency. Another aspect that helps keep the mill running as efficiently as possible, is its need to take material that has already been cut-to-length. Recently the mill has changed from selling chips and shavings in bulk, to prepackaged due to the higher profit margin. Other residues, or those unsold, are sent to a nearby biomass facility.

As many companies that have survived during the large downturn, Vaagen brothers understands the need to keep up production and provide what is currently in demand. The company is currently sporting a kiln capacity of around 250,000 bf and production goals of only a small 4-ft gap between each board.

Structurecraft:

This was an unplanned tour with the company, which is in Vancouver, British Columbia, Canada, that allowed us to see a middle man of the CLT world. While this company does not produce CLT, they do engineering, architectural, and custom cutting aspects for the product. It has an impressive balance of young and old employees, given that is not what is thought to be the current demographic of the timber industry.

A.5: Nordic Structures
Quebec, Canada
15-17 May, 2017
Host: David Croteau (Vice President of Operations), Sebastien Gauvin (Production Engineer)
Participants: Christina Lawrence and Gabriel Schwartzman (OSU student)

Nordic Structures was, at the time of the tour, the only CLT company that was established in North America on the East coast. With a sales office located in Montreal, Q.C. and the manufacturing site and sister company, Chantiers Chibougamau, in Chibougamau, Q.C. roughly eight hours north of the city. While the manufacturing is far from sales, it allows the company to be cost effective, not having to transport timber to a location where it will be further broken down and not transporting of the waste or unused material. Recently a second mill was added near the original. Since 2008, the company has done an estimated 1,000 projects, where commercial construction seemed to be the most popular use of the material.

The company is designed to help a customer from the beginning to the end of a project. This company model is further helped along with companies and organizations such as Wood Works in Quebec that help with general knowledge and education of CLT. As the company has the capability to manufacture Glulam and Cross-laminated Timber, it also can work with customers to build hybrid structures the use both products. This is particularly useful, according to the company, because of the spans that the two products can use—glulam ranges from 44 to 89 ft., while CLT can be produced to reach larger lengths (89+). While the price is depended on the individual project, an average range is between $19 to $20 per square foot of CLT. It was later further explained that this was the price to be cost competitive with the other construction materials. However, the company indicated that customers have difficulty seeing other points of cost savings throughout the construction process.

Timber used for Nordic’s products are harvested off of Crown lands, or Canadian’s version of government owned lands, and mainly consists of Black Spruce in a boreal forest setting. The sister company, Chantiers Chibougamau, is required to change harvesting sites every two weeks due to regulations in the area—this has hurt the company significantly as the timeframe was changed from every 2 years. Consumption of timber is anywhere from 30 to 40 “Mega loads” per day, which is equal to 3.5 times that of a typical load delivered to other mills. The lumber produced from this material results in little blue-stain presence. Current capacity of the CLT manufacturing facility is 80,000 ft^3, but production is only at 20,000 ft^3.

Glulam line: Glulam produced by the company uses the small end of timber that is harvested and produced 1x3’s and 1x2’s. Each lamella of the beams are stress graded and then glued together using a one part PUR resin with an open time of 4 mins. The beams are then CNC'd by one of three Suprema (Italian) CNC machines that consists of a seven-point axis.

CLT line: Nordic has worked to make their CLT line as efficiently as possible. After lumber has been finger jointed and cut to length, it is then labeled via a color in order for workers to have a quick and simple way to determine if a stack is correct or not. Wane that is present in the material is also directed to bend in one direction that best benefits the strength of the panel and is placed only within the middle lamellas of the panels. The company then uses a vacuum lift to move the prepared lumber into panel formation, where between each layer a Purbond adhesive was used that had a 10-20 minute open time allowed. Once the layup is complete, the panel is then rolled into the press where a pressure of 150 psi is applied. The company currently only uses a lengthwise side pressure and a top pressure, while working on including a width side pressure. The press is roughly 8 ft wide by 60 ft. in length.

APPENDIX B: W. Sept (2015) "Threshhold Action Tool"

This script was originally written by Warren Sept, a summer high school intern, for the use of PRF. It was later edited for use with PUR adhesive. This script is used along with the image analysis program ImageJ.

```
//Warren Sept
//July 1, 2015
macro "Threshold Action Tool - C037T3f20T"{
//let user select image and open it
path = File.openDialog("Choose Image");
open(path);
//save path without .jpg
newpath = substring(path,0,lengthOf(path)-4);
//save the name of the image
title = substring(getTitle(),0,lengthOf(getTitle())-4);
//let user select the area to be analyzed
setTool("polygon");
waitForUser("Make Selection");
158
158
//save coordinates of selection points
getSelectionCoordinates(xpoints, ypoints);
//create results folder
parent = File.getParent(path);
if(!File.isDirectory(parent+"\\Results\\")) {
File.makeDirectory(parent+"\\Results\\");
}
//crop for Selection
run("Crop");
run("Clear Outside", "stack");
//save cropped picture
```

```
saveAs("jpeg", parent+"\\Results\\"+title+"-crop.jpg");
//convert to RGB stack and delete red and blue slices
run("RGB Stack");
run("Delete Slice");
run("Next Slice [>]");
run("Next Slice [>]");
run("Delete Slice");
//optional save green slice
//saveAs("jpeg", newpath+"-green.jpg");
//finds the low point in the middle of the histgram
getHistogram(0,count,256);
min = count[100];
low=100;
for(x=500;x<150;x++){
if(count[x]<min){
min=count[x];
low=x;
}
}
//set the threshold to the high point
159
159
setThreshold(low,254);
//let the user change the threshold
run("Threshold...");
waitForUser("Set Threshold");
//selectWindow("Threshold");
run("Close");
//make custom table
f = "[Results]";
run("New... ", "name="+f+" type=Table");
```

```
print(f,"\\Headings:"+title+"\t");
//show the threshold values
getThreshold(lower,upper);
print(f,"lower\tupper");
print(f,lower+"\t"+upper);
//add up and show the pixels inside and outside the threshold
in=0;
out=0;
print(f,"in\tout");
for(x=lower;x<upper+1;x++){
in+=count[x];
}
for(x=0;x<lower;x++){
out+=count[x];
}
for(x=upper+1;x<256;x++){
out+=count[x];
}
print(f,in+"\t"+out);
//add in and out to get the total area
print(f,"area=\t"+(in+out));
//calculate and show the percent resin/wood
print(f,"%resin=\t"+(in*100)/(in+out));
print(f,"%wood=\t"+(out*100)/(in+out));
//show the selection points
print(f,"X\tY");
160
160
for(x=0;x<xpoints.length;x++){
print(f,xpoints[x]+"\t"+ypoints[x]);
}
```

```
//show the ammount of pixels for each red value
print(f,"value\tcount");
for(x=0;x<255;x++){
print(f,x+"\t"+count[x]);
}
//save the table as a .txt with the same name as the image
saveAs("measurements...", parent+"\\Results\\"+title+".txt");
//close table, threshold and image
run("Close");
run("Close");
}
```