SALVAGED LUMBER FOR STRUCTURAL MASS TIMBER PANELS: MANUFACTURING AND TESTING

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Abstract. Portland, OR, was the first US city to implement a deconstruction ordinance in 2016. Although salvaged lumber can have high demand, the market for small-sized lumber from deconstructed dwellings is near saturation. New applications for this material are required for market development, industry diversification, and increasing deconstruction practices. Mass timber products such as cross-laminated timber (CLT) could be a new market for this material, but presently there is minimal information qualifying the performance of mass timber panels made with salvaged lumber. Three, full-sized, 3-ply experimental panel layups, with varying amounts of salvaged/recycled wood content, were manufactured and tested to characterize panel properties. Manufacturing processes and testing methods followed ANSI/APA PRG 320-2018: Standard for Performance Rated Cross-Laminated Timber. Each panel layup had three replicates for nine panels in total. Panels measured 1.1 m by 2.3 m by 3 plys, and test results were used to calculate the effective flatwise bending moment resistance ($(F_bS)_{eff}$), effective flatwise bending stiffness ($(EI)_{eff}$), effective shear stiffness in flatwise bending ($(GA)_{eff}$), flatwise shear resistance (V_s), percent wood failure (WF%), and percent delamination (Delamination%). Results were compared with E3 grade 3-ply CLT panels made in the United States and indicated that salvaged lumber could be used as feedstock for mass timber panels in core layers or all layers. All panel layups passed benchmarks for $(F_bS)_{eff}$ and $(EI)_{eff}$ benchmarks with values greater than PRG 320. Panels having salvaged lumber in the core layer also met V_s benchmarks. Furthermore, all panels passed examination for WF% but struggled to meet delamination requirements. Possibilities exist for better performance if panels were made in a commercial setting. This research shows salvaged lumber has promise for manufacturing structural CLT, but more research and a larger sample size is needed to verify findings.

Keywords: Deconstruction, salvaged lumber, cross-laminated timber, structural performance, recycling, engineered wood products, wood composites.

INTRODUCTION

Although wood has a multitude of potential uses, about 60% of the virgin wood used in the United States is for new construction and residential repair and remodel. Within this use category, the major products include lumber, timber, flooring, siding, and other construction and remodeling materials (Howe et al 2013). Postservice life recovery for this material ranges between 10% and 11% and lags far behind the rates for steel (98%) and concrete (82%) (Falk and McKeever 2012; Bowyer 2016). Currently, more than 70 million tons of wood waste is generated annually

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in the United States, with more than 40% still available for recovery (Falk and McKeever 2012). The single greatest barrier that has been identified by wood reuse and recycling experts is the lack of market development for reused or recycled materials (Howe et al 2013).

Portland, OR, was the first city in the United States to adopt a deconstruction ordinance in October 2016 (Wood 2016). Deconstruction is the reverse process of construction with the goal of minimizing damage to construction materials and to retain material quality (Diyamandoglu and Fortuna 2015). The ordinance requires residential buildings, built before 1917 or designated a historic resource, which seek demolition permits to instead be deconstructed, unless deemed immediately dangerous or hazardous. Approximately one-third of the demolition permits submitted yearly are covered by this ordinance (Wood 2015).

Current market supply for material collected from Portland deconstruction practices is provided by both for- and nonprofit entities that have established retail outlets for materials. Market demand is strongly driven by reuse and the do-it-yourself ethic because of design aesthetics (Wood 2018). Use of salvaged material, specifically 2-by lumber, could potentially be reused structurally, but structural performance is a logical concern (Falk et al 2012). Falk et al (2008) explored this question by examining several thousand pieces of lumber salvaged from World War II military buildings. Salvaged lumber was visually graded on-site, and those meeting No. 2 and Select Structural grades were selected for further testing to determine residual bending strength and stiffness. Results from tests were compared with strength data from the in-grade lumber testing program (Green and Evans 1988). Salvaged lumber 5th percentile bending strength was found to be between 16% and 18% lower than the in-grade bending strength, but bending stiffness was about 10% higher (Falk et al 2008). In spite of the attractiveness of using salvaged lumber structurally, its acceptance into new construction applications is hampered because of grading and engineering design which are required by building code (Falk et al 2012).

Falk et al (1999) observed that damage and defects negatively affected the grade assigned in more than one-third of the lumber graded. However, the effects of localized defects in recovered wood can be minimized when used in a wood composite (Ross 2010) such as cross-laminated timber (CLT) panels or glulam. CLT panels are large wood composites capable of being used in structural applications. A recent study by Rose et al (2018) examined the potential of using waste timber from the construction industry to manufacture CLT, as well as test and model the effects of defects and reduced feedstock properties. Rose et al (2018) reported that there is no significant difference in compression stiffness between samples made with timber waste and those made with virgin lumber, but minor defects in timber waste do have an effect on bending stiffness.

The use of structural building materials is guided by building codes and accreditation services for reasons of life safety and liability. Before a new building product can be used in a structural application, it is necessary for the product to meet performance standards and/or show that the product is able to meet certain criteria (Karacabeyli and Douglas 2013; ANSI/APA 2018). For CLT, the ANSI/APA PRG 320-2018: Standard for Performance-Rated Cross-Laminated Timer sets benchmarks for CLT manufactured for structural use. The standard states the minimum requirements for all materials used to make CLT, as well as minimum acceptable panel properties. PRG 320 also allows for some flexibility in terms of different layup combinations and materials to be used in structurally rated CLT, providing the appropriate steps and testing needed for manufacturing of custom panels.

This study aimed to manufacture and characterize custom experimental mass timber panels using salvaged lumber from Portland residential building deconstruction in three exploratory 3-ply layups; all salvaged lumber (100%SL), salvaged lumber outer layers with 100% recycled content medium density fiberboard (MDF) core (SL-MDFcore), and virgin lumber outer layers with salvaged lumber core (VL-SLcore). Reasoning behind the selection of these three layups were associated with the potential to increase wood reuse and recycling by implementing these materials in the

manufacture of CLT or hybrid mass timber panels. Panels were manufactured and tested in accordance with ANSI/APA PRG 320-2018 to determine if salvaged lumber could be included in CLT panels as core stock or used to manufacture a 100% salvaged lumber CLT panel, expanding market opportunities for recovered lumber from Portland deconstruction.

MATERIAL AND METHODS

Materials for Mass Timber Panel Manufacture

A total of 265 Douglas fir (*Pseudotsuga menziesii*) 38 mm × 89 mm (2 × 4) boards of salvaged lumber, 84 pieces of Douglas fir 38 mm × 98 mm × 2.4 m No. 2 virgin lumber, and three Trupan VESTA NAF MDF panels (1.2 m × 2.4 m × 25.4 mm), which were made with 100% recycled/recovered wood content, were used to manufacture mass timber panels. Salvaged lumber was nondestructively MSR (machine stress rated) graded using a Metriguard Model E-computer and visual defects (damage, knots, and rot) recorded (Arbelaez et al 2019).

A polyurethane adhesive (LOCTITE HB X452 PURBOND) and an aqueous primer solution for conditioning wood surfaces (LOCTITE PR 3105 PURBOND) were used for the manufacture of mass timber panels. LOCTITE HB X452 PURBOND has an assembly time of 45 min and a curing/pressing time of 112 min. LOCTITE PR 3105 PURBOND primer solution aids adhesive penetration and was diluted with 90% deionized water before being misted onto all surfaces to be adhered 15 min before adhesive application. We used a spread rate of 180 g/m^2, a contact cement roller for spreading adhesive, and a press force of 758.4 KPa.

An in-house CLT press was used to manufacture panels. This CLT press was designed by one of the coauthors to meet current ANSI/APA PRG 320 manufacturing guidelines. The press has a total area of 1.4 m by 2.4 m. The press has five steel I beam segments (each 228 mm wide, 2.4 m long, and 25.4 mm apart); with each operated by a pair of hydraulic cylinders rated at 34.4 MPa and an operating pressure of 689 KPa per cylinder.

Manufacturing

Each layup had three replicates, for a total of nine panels. Panels were made individually, and all pieces of lumber for the selected panel to be made
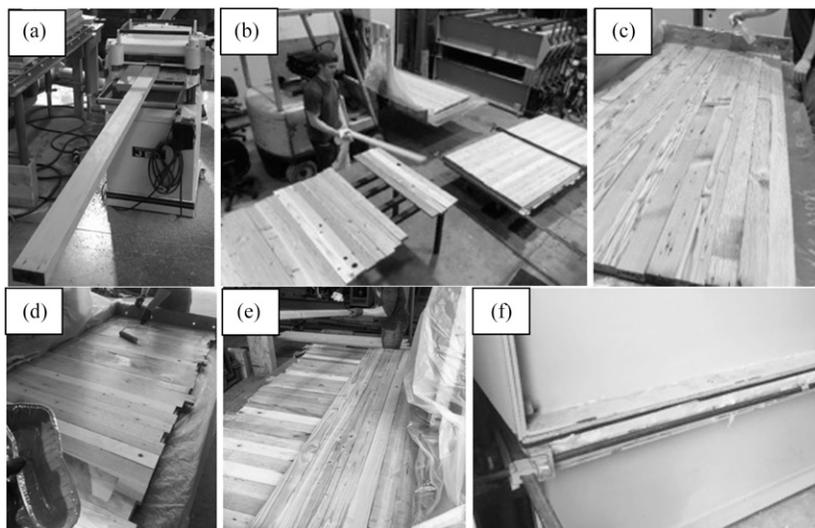

Figure 1.   Panel manufacturing process: (a) planning a fresh face, (b) followed by organizing and cleaning laminations, (c) misting surfaces, (d) applying and spreading adhesive, (e) laying up panels, and (f) loading press.

that day received a fresh face within 24 h of panel manufacturing (planed to the final target thickness). All pieces of lumber chosen (salvaged or virgin) for the major direction of panels were planed to a final thickness of 36 mm. Final thickness of boards selected for core layer, minor direction, was 22 mm (Fig 1[a]). Sanded MDF panels were used as is and were only cut to length and wiped clean before use in panel manufacturing.

Before assembling panels, laminations were organized and labeled (Fig 1[b]) before all surfaces to be adhered were misted with the primer solution 15 min before applying adhesive (Fig 1[c]). Once misted, and after 15 min, the first layers of boards were placed on an assembly sheet and adhesive was applied. Following adhesive application on the first layer, minor direction boards were placed perpendicularly to the last (for 100%SL and VL-SLcore panels) (Fig 1[d]). After all minor direction boards were placed on the first layer, the adhesive application process was repeated, and the final layer of boards were placed perpendicularly to the minor layer to complete the three layers (Fig 1[e]).

The panels were pressed with a force of 758 KPa for 210 min to ensure proper bonding (Fig 1[f]). Although the allowable open-time for the adhesive is 45 min, the average time taken from the moment the adhesive was weighed to the time the panel was under the target pressure was 30 min.

Sample Extraction and Testing

After manufacturing, the panels were stored indoors at 20°C and 36% RH for at least 24 h. The panels were then cut to their final dimensions (1.1 m by 2.3 m by 3 plys) and the prepanel qualification cutting diagram from PRG 320 was referenced for test sample extraction. Two long-span bending samples, two short-span bending samples, three block shear samples, and three cyclic delamination samples were cut per panel (Fig 2).

Bending samples. Long-span and short-span bending samples measured 2.3 m long by 0.3 m wide by 3 plys deep and 0.54 m long by 0.3 m
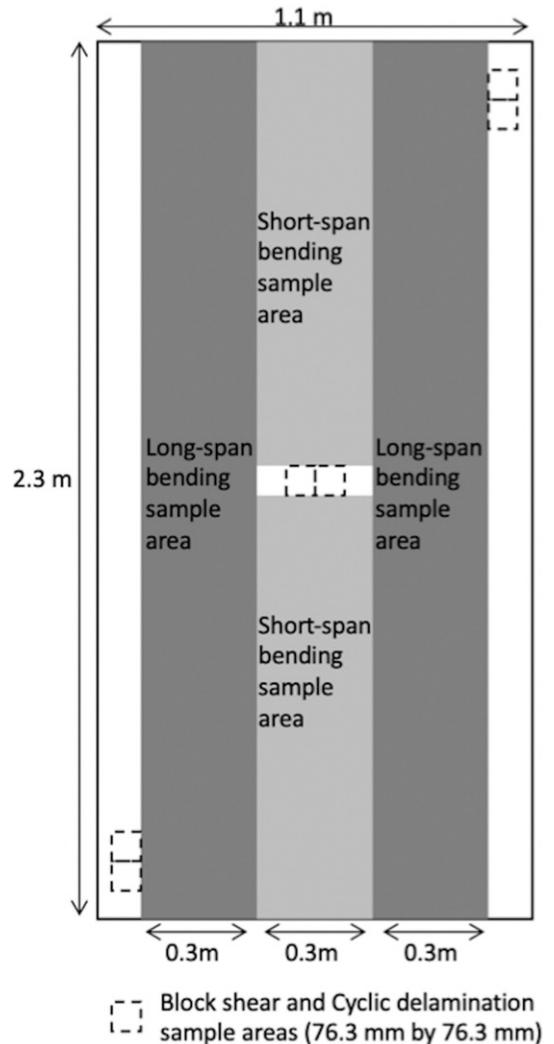

Figure 2. CLT panel cutting diagram followed for sample extraction.

wide by 3 plys deep, respectively. Testing procedures for bending samples followed ASTM D4761 Section 8. Bending tests were conducted using a universal testing machine (UTM) and MTS actuator. Long-span tests used third point loading, whereas short-span used center point, and the actuator ramp rate was of 7.6 mm/min for long-span bending and 2.5 mm/min for short-span bending. All samples were loaded until failure (Fig 3). Load and deflection data (actuator and bridge deflection) was continuously
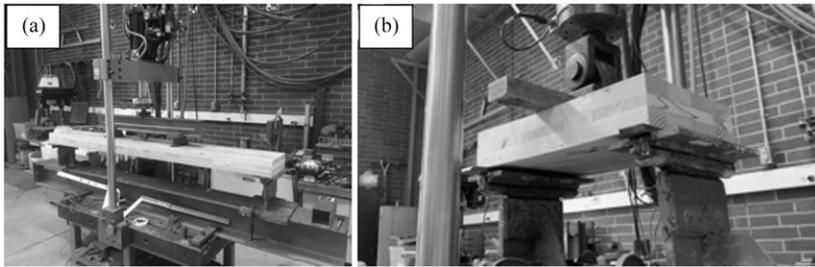
Figure 3.   (a) Long-span third-point bending test setup and (b) short-span center-point bending test setup.

collected. Although a span-to-depth ratio of 21 was used for long-span bending tests, ANSI PRG 320 recommends a span-to-depth ratio of approximately 30. This is a deviation from PRG 320, but previous studies have also deviated from this because of infrastructural limitations (Kramer et al 2013).

Block shear samples. Block shear tests were performed in accordance with PRG 320-2018, which refers to American Institute of Timber Construction Test (AITC) T107-2007 "Shear Test" that is commonly used to examine structural glue-laminated timber (AITC 2007) (Fig 4[a]). Before testing, block shear samples were conditioned for more than 2 wk in a standard room at 20°C and 65% RH to provide a sample MC of 12% at the time of testing. The tests were conducted on a UTM equipped with a 10-kN load cell (Fig 4[b]). Each test was conducted at a rate of 0.9 mm/min and loaded until failure. After completing the tests, red safranin was used to stain the transparent PUR bond line to calculate percent wood failure. Once stained, transparent

5 mm × 5 mm grid paper was used to quantify the percent wood and adhesive failure per sample (red meaning wood failure and clear meaning adhesive failure) (Fig 4[c]).

Cyclic delamination samples. Cyclic delamination followed procedures stated in the AITC Test T110-2007 "Cyclic Delamination Test" as stated by ANSI/APA PRG320-2018 (AITC 2007). Dimensions of test samples were 76.3 mm wide by 76.3 mm long by 3 plys deep (Fig 5[a]). Like block shear samples, cyclic delamination samples were also conditioned to 12% MC before testing. The procedure used for the cyclic delamination test consists of three parts; a vacuum (at 510-640 mm Hg for 30 min)/pressure soak cycle (517 ± 34 KPa for 120 min) in a pressure vessel, followed by a rapid drying cycle in an oven at 71 ± 3°C and until mass was within 15% of initial mass (time required can be 10-15 h), and then inspection of delamination (Fig 5[b] and [c]).
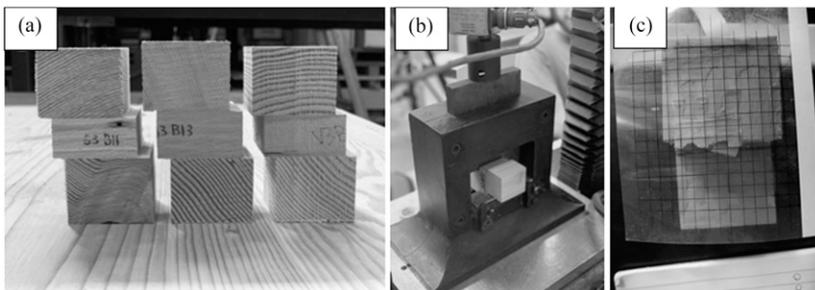

Figure 4.   (a) Block shear "stair-step" samples based on the AITC Test T107-2007, (b) loaded block shear test setup, and (c) failure plane examination using red safranin stain and transparent grid paper (AITC 2007).
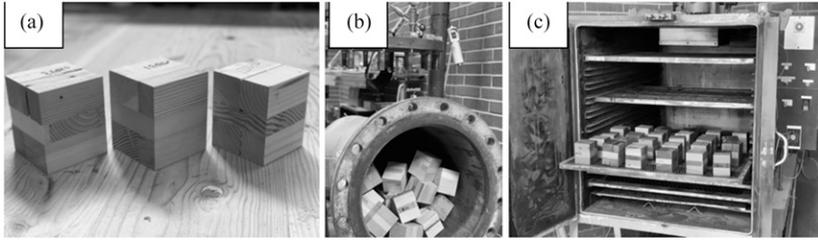
Figure 5.   (a) Cyclic delamination samples based on the AITC Test T110-2007, (b) pressure cylinder used for vacuum/pressure soak cycle, and (c) oven used for rapid drying cycle (AITC 2007).

Calculations

The properties considered in this study include effective flatwise bending moment resistance $((F_bS)_{eff})$, effective flatwise bending stiffness $((EI)_{eff})$, effective shear stiffness in flatwise bending $((GA)_{eff})$, flatwise shear resistance (V_s), percent wood failure (WF%), and percent delamination (Delamination%) in the major direction. Long-span bending test data were used for calculating the effective flatwise bending moment resistance and stiffness, short-span data for calculating flatwise shear resistance, block shear for percent wood failure, and cyclic delamination for percent delamination. The effective shear stiffness was calculated using the manufacturer's shear stiffness values for MDF and virgin lumber, and the average shear stiffness values calculated after converting dynamic stiffness values recorded while grading individual salvaged lumber pieces.

Effective flatwise bending moment resistance $((F_bS)_{eff})$. After completing long-span bending tests and collecting data, the formula shown in the CLT Handbook was used to calculate $(F_bS)_{eff}$. This formula uses maximum load and span of samples for calculating the maximum moment, which is also equal to the effective flatwise moment resistance. For design, the induced bending moment must be less than or equal to the moment capacity. Therefore, the maximum moment can be calculated to find $(F_bS)_{eff}$ (Karacabeyli and Douglas 2013). The equations used appeared as follows:

$$F_b'S_{eff} \;\; M_b/M_{max} = \frac{P_{max}l}{6} \div b = (F_bS)_{eff} \;\; , \quad (1)$$

where P_{max} is the maximum load at failure, l is the span, and b is the width of the sample.

Effective flatwise bending stiffness $((EI)_{eff})$. Deflection and load data, recorded by the actuator, were used to determine effective flatwise bending stiffness. The equation used for calculation references the National Design Specification for Wood Construction (NDS) shear moment diagram for a simple beam with two equal concentrated loads symmetrically placed (ANSI/AF&PA 2005):

$$(EI)_{eff} = \frac{Ka}{24}\left(3l^2 - 4a^2\right) \div b, \quad (2)$$

where l is the span, a is the distance between load point and bearing plate, K is the slope of the linear region of the load–deflection curve between 20% and 40% of the maximum load, and b is the width of the sample.

Effective shear stiffness in flatwise bending $((GA)_{eff})$. Equations available in the CLT Handbook were used for calculating the effective shear stiffness in flatwise bending of samples. Because the equation for the effective shear stiffness in flatwise bending accounts for the properties of individual layers in a panel, the average calculated stiffness of salvaged boards, measured with Metriguard, and product stiffness values were used to calculate G_i. For calculating G_i, PRG 320 assumes that $G = E/16$ for laminations in the major direction and $G_i = E/(16 \times 10)$ for the minor direction, to account for rolling shear. Steps taken for finding the effective shear

stiffness in flatwise bending follow the CLT Handbook and use the following equation for a 3-ply panel (Karacabeyli and Douglas 2013):

$$(GA)_{eff} = \frac{a^2}{\frac{h_1}{2G_1 b_1} + \frac{h_2}{G_2 b_2} + \frac{h_3}{2G_3 b_3}}, \quad (3)$$

where a is the distance between extreme fibers in the cross-section, h_i is the thickness of individual panel layers, G_i is the stiffness of individual layers, and b_i is the width of each layer of the test sample.

Flatwise shear resistance (V_s). Short-span bending test data were used for calculating flatwise shear resistance. The formula used was the following:

$$V_s = \frac{VQ}{Ib} \times l, \quad (4)$$

where V is the maximum load at failure divided by 2, Q is the moment area above the section of interest, I is the moment of inertia, b is the width of the sample, and l is the span.

Percent wood failure (WF%). Percent wood failure was calculated after completing all block shear tests and staining the failure plane of samples. After determining the shear plane area and glue failure area using the transparent grid paper, recorded data were used in the following equation to determine percent wood failure:

$$WF\% = 1 - \left(\frac{\text{Grid Area}_{not\,red}}{\text{Grid Area}_{total}} \times 100\% \right). \quad (5)$$

Percent delamination (%). After cyclic delamination samples reached a mass within 15% of their initial mass and removed from the oven, they were examined for delamination. ANSI defines delamination as the separation of layers in a laminate because of failure of adhesive. Percent delamination was determined by measuring the total circumference of bond lines, as well as measuring the length of delamination areas. Recorded

measurements were then used to calculate percent delamination using the following equation:

$$\text{Bondline Delamination}\,(\%)$$
$$= \frac{\text{Bondline Length}_{delamination}}{\text{Bondline Length}_{Total}} \times 100\%. \quad (6)$$

RESULTS

Nine exploratory 3-ply mass timber panels (dimensions were 1.14 m by 2.28 m by 3 plys) were manufactured using salvaged lumber from Portland residential building deconstruction. The 3-ply layups were 1) 100%SL, 2) SL-MDFcore, and 3) VL-SLcore. Each panel was cut to provide two long-span bending, two short-span bending, three block shear, and three cyclic delamination samples that were tested following ANSI/APA PRG 320-2018 guidelines.

Results Summary

Table 1 summarizes the average values for each criterion considered by panel type. Also listed in Table 1 are the benchmark values of E3 grade of CLT as ANSI PRG 320 converted from ASD design values to characteristic values as per the factors provided in Table 1 of ANSI APA PRG 320-2018. According to Table 1, no panel layup type was able to pass all the criteria for E3 grade 3-ply CLT panels as per ANSI/APA PGR 320-2018. Not considering the delamination values, for both 100%SL and VL-SLcore, the properties were above the benchmark values for grade E3. SL-MDFcore did not meet the shear stiffness and shear resistance benchmark. This was expected because shear flow is essentially through the core material and MDF is a weaker material in shear than solid lumber; hence, yielding a weaker panel in shear. With advances and changes in adhesive technologies and manufacturing settings for this particular application, it is possible to reduce the Delamination% in the future.

Testing Results

Bending tests. For the long-span samples, failure type, maximum load at failure, and deflection varied among samples. Figure 6(a) presents the

Table 1.   Average results for each experimental panel layup compared with the ANSI/APA PRG 320-2018 E3 grade 3-ply panel after taking converting design values to test values for $(F_bS)_{eff}$ and Vs as per the ANSI/APA PRG.

Panel layup	$(F_bS)_{eff}$ (N-mm/m of width) and CoV%		$(EI)_{eff}$ (N-mm^2/m of width) and CoV%		$(GA)_{eff}$ (N/m of width) and CoV%		V_s (kN/m of width) and CoV%		WF% and CoV%		Delamination% and CoV%	
3-ply E3 grade CLT panel	2.62E+07		7.63E+11		5.11E+06		51.02		>80.0%		<5%	
100% salvaged lumber	6.41E+07	26%	2.08E+12	6%	1.12E+07	2%	57.96	6%	99.0%	3.0%	8.6%	104%
Virgin wood/salvaged core	8.04E+07	6%	2.04E+12	8%	1.05E+07	3%	59.41	7%	99.9%	0.0%	10.8%	70%
Salvaged wood/MDF core	3.74E+07	35%	2.23E+12	8%	2.11E+06	1%	35.95	21%	99.9%	0.0%	1.9%	294%

typical load–deflection curve for the three types of panels tested. As seen from the figure, the stiffness of the samples are comparable (also evident from Table 1), but the maximum load
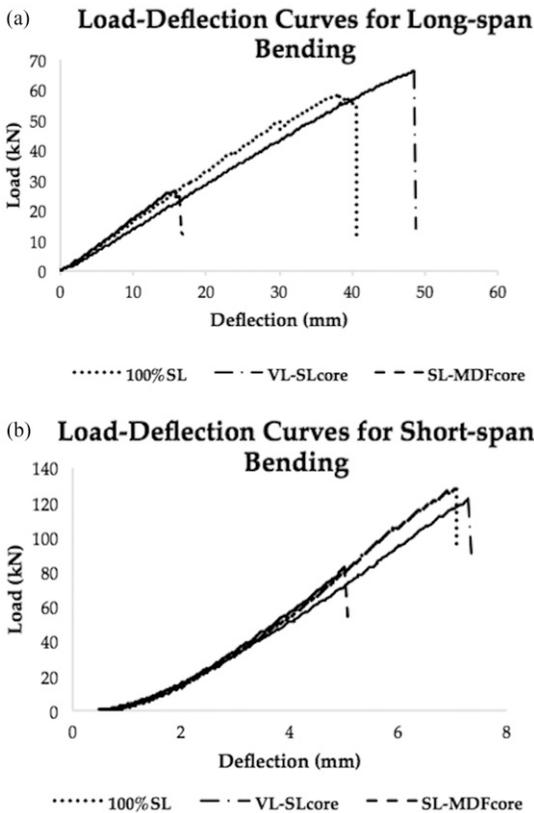

Figure 6. (a) Example of long-span bending load–deflection curves for a sample of each panel type and (b) example of short-span bending load–deflection curves for a sample of each panel type.

varied. The panels with MDF core exhibited lower strength than the other two types. The average maximum load was 54 kN with a range from 37 kN to 70 kN for 100%SL panel samples, 32 kN with a range from 20 kN to 46 kN for samples from SL-MDFcore panels, and 67 kN with a range of 63 kN to 71 kN for samples from VL-SLcore panels. Total average deflection at maximum load for samples from 100%SL panels and VL-SLcore panels was 48.5 mm and 49.7 mm, respectively, whereas the average deflection of samples from SL-MDFcore panels was only 19.3 mm. The highest and lowest total deflection, recorded at the maximum load, was 55.7 mm and 12.4 mm, respectively. Samples from 100%SL panels all failed in tension (mostly where defects were present), all samples from SL-MDFcore panels failed in rolling shear (through the middle of the MDF), and four of the six samples from VL-SLcore panels failed in tension, whereas the others failed in rolling shear of the middle layer. Maximum load applied at failure varied from 20 kN, for one of the samples from an SL-MDFcore panel, to 71 kN, for a sample from one of the VL-SLcore panels. Samples from 100%SL panels and VL-SLcore panels resisted higher loads on average than samples taken from SL-MDFcore panels.

All short-span bending samples failed in shear with maximum load ranging from 62 kN to 143 kN. The average maximum load for samples from 100%SL and VL-SLcore panels was similar at 126 and 127 kN, respectively, and lower for samples from SL-MDFcore panels (82 kN). Likewise, average cylinder deflection at maximum load for

samples taken from the 100%SL and VL-SLcore panels were comparable, but samples from SL-MDFcore panels showed substantially lower deflections at maximum load (Fig 6[b]).

Block shear test. On average, block shear samples from 100%SL panels resisted the greatest load before failure, at 8.7 kN, with a range between 4.9 kN and 15.3 kN. VL-SLcore panels layers provided samples that had the second highest average maximum load, at 7.7 kN, but also showed less variability with a maximum load range between 6.0 kN and 9.4 kN. Samples from SL-MDFcore panels resisted the least average maximum load, at 6.8 kN, with a range between 4.8 kN and 9.0 kN.

Cyclic delamination test. Data recorded during cyclic delamination tests were associated with changes in mass due to water adsorption/desorption and samples (assumed conditioned MC 12%) were tested together and received the same treatment. After completing the pressure soak cycle, samples from VL-SLcore panels had the highest average moisture uptake increasing in weight to 116% of the initial mass, and 100%SL panel samples had the second highest average moisture uptake (103%), whereas samples from SL-MDFcore panels had the lowest (102%). After 15 h of drying, the average percentage of moisture still left in samples was similar for samples from VL-SLcore panels and SL-MDFcore panels at 14% of the original mass. All samples from 100%SL panels showed greater drying with an average remaining moisture being 11% of the original mass.

Calculation Results

Calculated values were used for comparing with the E3 Grade 3-ply CLT panel, ASD reference design values for CLT in the United States, published in ANSI/APA PRG 320-2018, after converting them to characteristic test values as per the factors provided in ANSI/APA PRG 320-2018 (Table 1) and bond qualification criteria.

Effective flatwise bending moment resistance $((F_bS)_{eff})$. VL-SLcore samples had the highest average $(F_bS)_{eff}$ at 80.4 10^6 N-mm/m of width, samples from SL-MDFcore panels had the lowest average (37.4 10^6 N-mm/m of width), whereas the average for samples from 100%SL panels was 64.1 10^6 N-mm/m of width. Variability between samples of the same panel type was also lowest between samples from VL-SLcore panels (74.9-85.4 10^6 N-mm/m of width) and highest between samples taken from 100%SL panels (43.7-82.9 10^6 N-mm/m of width).

The $(F_bS)_{eff}$ design value published in ANSI/APA PRG 320-2018 for E3 grade 3-ply CLT panels manufactured in the United States is 12.5 10^6 N-mm/m of width. For a direct comparison with PRG values, the published design values in PRG 320 were multiplied by 2.1 for converting design values, which take safety factors into consideration, to actual reference test values. After calculating reference values, the average performance of all panel types met the value for $(F_bS)_{eff}$.

Effective flatwise bending stiffness $((EI)_{eff})$. All panels had similar calculated $(EI)_{eff}$ values, with samples from SL-MDFcore panels being the stiffest. Average $(EI)_{eff}$ for each panel type were 208 10^{10} N-mm^2/m of width (100%SL), 223 10^{10} N-mm^2/m of width (SL-MDFcore), and 204 10^{10} N-mm^2/m of width (VL-SLcore). Individual $(EI)_{eff}$ values ranged from 178 10^{10} N-mm^2/m of width (for a sample from a VL-SLcore panel) to 248 10^{10} N-mm^2/m of width (for a sample from an SL-MDFcore panel). ANSI/APA PRG 320-2018 $(EI)_{eff}$ benchmark for E3 grade 3-ply CLT panels manufactured in the United States is 76.3 10^{10} N-mm^2/m of width. All samples had a calculated $(EI)_{eff}$ at least twice that of the ANSI/APA PRG 320-2018 benchmark.

Effective shear stiffness in flatwise bending $((GA)_{eff})$. Samples from 100%SL panels and samples from VL-SLcore panels had similar $(GA)_{eff}$ values, whereas samples from SL-MDFcore panels had much lower values. The calculated average $(GA)_{eff}$ values for all samples from each panel type were 11.2 10^6 N/m of width

(100%SL), 2.1 10^6 N/m of width (SL-MDFcore), and 10.5 10^6 N/m of width (VL-SLcore). Individual samples within the same panel type had similar $(GA)_{eff}$ values, and values between panel types did not overlap. The ANSI/APA PRG 320-2018 $(GA)_{eff}$ benchmark for E3 grade 3-ply CLT panels manufactured in the United States is 5.11 10^6 N/m of width, and only SL-MDFcore panel samples failed to meet $(GA)_{eff}$ benchmark values.

Flatwise shear resistance (V_s). Samples from 100%SL panels and VL-SLcore panels performed similarly with average V_s of 57.96 and 59.41 kN/m of width, respectively. Likewise, the ranges of values of samples from 100%SL panels (52.76-63.13 kN/m of width) and VL-SLcore panels (53.39-66.50 kN/m of width) were similar. Samples from SL-MDFcore panels, by contrast, had the lowest average V_s (35.95 kN/m of width) and greatest variability between samples ranging from 27.25 kN/m of width, the lowest value among all calculations, to 48.75 kN/m of width.

The V_s design value set by the ANSI/APA PRG 320-2018 for 3-ply E3 grade CLT manufactured in the United States is 16.20 kN/m of width. Like for $(F_bS)_{eff}$, the V_s design values in PRG 320 needed to be adjusted for comparison with reference test values. Published design values for V_s were multiplied by 3.1 to obtain reference values, as per the ANSI/APA PRG 320. Once the design values were converted to reference values, all panels from 100% SL and VL-SLcore panel types met the published V_s benchmark. The best performing panel was a VL-SLcore panel with a V_s equal to 66.50 kN/m of width followed by a 100%SL panel with 63.13 kN/m of width. None of the SL-MDFcore panels met the calculated reference test value for V_s. The lowest performing panel was an SL-MDFcore panel, having a V_s of 27.25 kN/m of width.

Percent wood failure (WF%). All samples showed less than 10% glue failure, with the highest being 9.7%. Overall average wood failure was above 99%, and a 100%SL panel had the poorest performance with an average WF% of 91.3%. The ANSI/APA PRG 320-2018 criteria specifies that all sample groups must have an average WF% greater than or equal to 80%; hence, all samples met minimum qualifications.

Percent delamination (%). SL-MDFcore panels had the lowest average delamination (1.9%), as well as the lowest variability between samples with the exception of one outlier (16.4% delamination). By contrast, samples from the other panel types showed higher average percent delamination (8.6% and 10.8% for 100%SL and VL-SLcore panels, respectively) as well as greater variability among samples. Range of percent delamination values for samples from 100%SL panels (0-23.4%) and VL-SLcore panels (0-24.2%) were similar. The ANSI/APA PRG 320-2018 qualifications for delamination require that all samples within a group show less than or equal to 5% delamination; based on this criterion, only one 100%SL met PRG delamination requirements.

DISCUSSION

Portland's deconstruction ordinance allows for quality building materials to be salvaged instead of landfilled. Markets are available for salvaged wood but are inefficient, and concerns of market saturation exist. We tested mass timber panels manufactured using salvaged lumber feedstock to determine if its performance was sufficient for it to be a viable product option. Panels were manufactured and tested in accordance with the ANSI/APA PRG 320-2018 and results compared with values published (after adjustments) in performance standards for E3 grade 3-ply CLT panels.

Along with salvaged lumber, the potential of manufacturing structurally rated mass timber panels with an MDF core was also explored. MDF was selected because it is a wood composite that can be made using 100% post-consumer recycled content and more homogenous than lumber. Although MDF is not a structural product, there is promise for it to be used with salvaged lumber to make an appearance grade mass timber panel, providing an additional potential market.

All short-span bending samples tested well and behaved predictably with shear failures throughout. Maximum load at failure and deflection for samples from 100%SL panels and VL-SLcore panels were similar. As both panel types contained a salvaged lumber core that failed in rolling shear, similar performance in short-span bending can be expected.

Long-span bending tests results were more variable than short-span bending tests. All samples from VL-SLcore performed similarly unlike samples from 100%SL panels and SL-MDFcore panels. Some variability between samples can be explained by the material in outer layers because bending stresses during tests are highest there. Defects and material properties of individual boards are more consistent in virgin lumber than salvaged lumber. Some samples from 100%SL panels failed at defects, whereas VL-SLcore samples did not. Consistent with Rose et al (2018), this supports findings that localized defects, such as large knots, in salvaged lumber used in the outer layer of CTL panels can play a role in performance. Although the third-point bending test method was used to promote tension failure, all long-span bending samples from SL-MDFcore panels failed in rolling shear as expected as MDF has inferior shear characteristics compared with lumber. Compared with a similar study carried out for investigating the use of low-value lumber from small-diameter timber for CLT production, the average maximum load resisted before failure for 100%SL and VL-SLcore was approximately 1.6 and 2 times greater than that for mixed species 3-ply CLT panels, respectively (Lawrence 2017).

Block shear samples from VL-SLcore panels and SL-MDFcore panels performed similarly in tests, whereas samples from 100%SL panels showed greater variability. All samples consistently showed high percentages of wood failure. Samples taken from SL-MDFcore panels cleanly sheared in the MDF layer. Larkin (2017) investigated the bonding parameters of hybrid CLT made with lower value lumber, as well as various adhesive types and pressing forces. Compared with Larkin (2017), our average percent wood

failure for each panel layup was at least 3% greater.

Observations made during cyclic delamination tests differed among panel types. Samples from SL-MDFcore panels consistently delaminated in the center of the MDF layer during cyclic delamination tests. Failure within the MDF layer explains why samples from SL-MDFcore panels showed much lower percent delamination than the samples from other panel types, which is why none of the SL-MDFcore samples were considered as passing the delamination test. An important observation is the difference in water adsorption/desorption between samples from 100%SL panels and samples from VL-SLcore panels. Although test samples had approximately the same dimensions, contained the same core layer material, and received the same test treatments, the average percent initial mass after pressure soak was 13% higher for samples from VL-SLcore panels. Lower moisture uptake of samples from 100%SL panels could be a result of fewer available hydroxyl bonding sites in wood because of a century of equilibration in service. The lower moisture uptake of samples from 100% SL panels could also be an explanation to a lower average percent delamination.

The CLT Handbook was frequently referenced for calculating sample testing performance. An interesting observation made when calculating benchmark criteria was that although samples from SL-MDFcore panels were not as strong in bending as other samples (having a lower effective flatwise bending moment resistance $(F_bS)_{eff}$), it was stiffer on average (having a higher effective flatwise bending stiffness $(EI)_{eff}$). The equations provided by the CLT Handbook for calculating $(GA)_{eff}$ took properties of individual pieces of lumber into consideration. Although all pieces of lumber were evaluated individually and their respective properties were known, the exact location of these pieces were not recorded. Hence, general averages for properties were determined and used for calculating $(GA)_{eff}$. Furthermore, because the calculation for $(GA)_{eff}$ solely used material properties, SL-MDFcore panels would never achieve a sufficiently high

enough $(GA)_{eff}$ value because of the lower elasticity properties of the MDF material used.

Results and observations indicate that salvaged lumber could be used as feedstock for mass timber panels in core layers or all layers to meet mechanical performance requirements. Consistent with the findings from Kramer et al (2013), which looked at using low-density hardwoods (hybrid poplar) for CLT applications, the results from long- and short-span bending tests were promising. Based on the exploratory findings of this study, it is likely that panels made with salvaged material could meet and exceed shear and bending requirements for the ANSI/APA PRG 320-2018 E3 grade CLT. Furthermore, the results from panels containing salvaged material could present an opportunity to reduce landfill pressures and pressures on forests, while also expanding wood waste markets.

Other than delamination, the average results for 100%SL panels and VL-SLcore panels met all other E3 grade 3-ply CLT benchmarks. Furthermore, delamination results from cyclic delamination tests are used as indicators for measuring the performance and effectiveness of panel manufacturing operations, not mechanical properties. It is likely that percent delamination results of panels containing salvaged material could be improved if made in a commercial mass timber panel manufacturing facility and/or if automation of manufacturing processes were available. Despite the positive results, more research is needed on mass timber panels using an alternative raw material such as salvaged lumber to be sure of its structural and manufacturing performance.

Some of the variability in the data can be attributed to manufacturing operations. All mass timber panels used for this study were made in-house using the same adhesive and methodology between panels. Every step taken in the manufacturing process was either carried out or controlled manually. If the opportunity arose to repeat this study, the glue spreader, panel assembly line, and press should all be automated to maintain consistency between panels and reduce human error. Likewise, the potential of human error was also present in sample preparation. To avoid this in future studies, a computer numerically controlled machine should be used to cut samples.

CONCLUSIONS

The goal of this study was to manufacture and test custom experimental mass timber panel layups containing salvaged lumber. All experimental panel layups were 3 plys thick and either made with all salvaged lumber (100%SL), salvaged lumber for outer layers with MDF core (SL-MDFcore), or virgin lumber outer layers with salvaged lumber core (VL-SLcore). Procedures for manufacture and testing of panels followed the ANSI/APA PRG 320-2018: Standard for Performance-Rated CLT. Panel benchmarks and qualification criteria considered were effective flatwise bending moment resistance $((F_bS)_{eff})$, effective flatwise bending stiffness $((EI)_{eff})$, effective shear stiffness in flatwise bending $((GA)_{eff})$, flatwise shear resistance (V_s), percent wood failure (WF%), and percent delamination (Delamination%).

Our results indicate that salvaged lumber could be used as feedstock for mass timber panels in core layers or all layers. Other than delamination, the results for 100%SL panels and VL-SLcore panels met all E3 grade 3-ply CLT benchmarks as per ANSI/APA 320-2018. It is likely that the percent delamination results of panels containing salvaged material could be improved if made in a commercial mass timber panel manufacturing facility and/or if automation of manufacturing processes were available. More testing and a larger sample size is needed, but exploratory results were promising for the use of salvaged material in mass timber.

and Henkel for providing MDF panels, virgin lumber, and polyurethane adhesive, respectively.

REFERENCES

AITC (2007) Test methods for structural glued laminated timber. American Institute of Timber Construction, Portland, OR.

ANSI/AF&PA (2005) National design specification for wood construction (NDS). American National Standards Institute/American Forest and Paper Association NDS. American Wood Council, Washington, D.C.

ANSI/APA (2018) Standard for performance-rated cross-laminated timber. ANSI/APA-PRG320. American National Standards Institute, Tacoma, WA.

Arbelaez R, Schimleck L, Dahlen J, Wood S (2019) Evaluation of lumber from deconstructed Portland residential buildings. Wood Fiber Sci 51(4):1-9.

Bowyer J (2016) The irresponsible pursuit of paradise. Levins Publishing, Minneapolis, MN.

Diyamandoglu V, Fortuna L (2015) Deconstruction of wood-framed houses: Material recovery and environmental impact. Resour Conserv Recycl 100:21-30.

Falk R, Cramer S, Evans J (2012) Framing lumber from building removal: How do we best utilize this untapped structural resource? Forest Prod J 62:492-499.

Falk R, DeVisser D, Cook S, Stansbury D (1999) Effect of damage on the grade yield of recycled lumber. Forest Prod J 49:71-79.

Falk R, Maul D, Cramer S, Evans J, Herian V (2008) Engineering properties of Douglas-fir lumber reclaimed from deconstructed buildings. Research Paper FPL-RP-650. U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI. 47 pp.

Falk R, McKeever D (2012) Generation and recovery of solid wood waste in the U.S. Biocycle 53:30-32.

Green D, Evans J (1988) Mechanical properties of visually graded dimension lumber, Vol. 4. Southern pine. Pub. PB-88-159-413. National Technical Information Service, Springfield, VA.

Howe J, Bratkovich S, Bowyer J, Frank M, Fernholz K (2013) The current state of wood reuse and recycling in North America and recommendations for improvements, wood reuse and recycling in North America. Dovetail Partners, Minneapolis, MN.

Karacabeyli E, Douglas B (2013) CLT handbook, U.S. edition. FPInnovations and Binational Softwood Lumber Council, Point-Claire, Quebec.

Kramer A, Barbosa A, Sinha A (2013) Viability of hybrid poplar in ANSI approved cross-laminated timber applications. J Mater Civil Eng 26(7):06014009.

Lawrence C (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. MS thesis, Oregon State University, Corvallis, OR. 112 pp.

Larkin B (2017) Effective bonding parameters for hybrid cross-laminated timber (CLT). MS thesis, Oregon State University, Corvallis, OR. 120 pp.

Rose C, Bergsagel D, Dufresne T, Unubreme E, Lyu T, Duffour P, Stegemann J (2018) Cross-laminated secondary timber: Experimental testing and modelling the effect of defects and reduced feedstock properties. Sustainability 10:4118.

Ross R (2010) Wood handbook: Wood as an engineering material. General Technical Report FPL-GTR-190. U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI. 509 pp.

Wood S (2016) City of Portland ordinance no.187876, Portland, OR. https://www.portlandoregon.gov/bps/article/586234 (6 July 2016).

Wood S (2015) City of Portland resolution no. 37190, Portland, OR. https://www.portlandoregon.gov/bps/article/569831 (17 February 2016).

Wood S (2018) Deconstruction program (May 2018), U.S. Environmental Protection Agency. https://www.epa.gov/sites/production/files/2018-05/documents/epa_webinar_april_2018.pdf (20 August 2019).