The United States generates over 70 million tonnes of wood waste annually, with over 27 million tonnes still available for recovery. Current recycling rates for wood waste are in the range of 10% to 15%, which is much lower than other common building materials and indicative of an underutilized resource. Available markets for wood waste depend on material quality, quantity, and accessibility and are primarily for lower value uses. The greatest barrier identified to better wood recovery and reuse is a lack of end markets and market development. Creating a value-added product, in this thesis cross-laminated timber (CLT), using salvaged lumber could expand market opportunities for wood waste. CLT is an engineered wood panel made using layers of lumber glued in perpendicular directions and used as prefabricated walls and floors.

For salvaged lumber to be qualified for use in structurally rated CLT panels, it must be graded and selected based on Standards for Performance-Rated Cross-Laminated Timber ANSI/APA PRG 320-2018 lamination requirements. Likewise, American National Standard ANSI/APA PRG 320-2018 specifies the required qualification criteria and benchmarks that panels must meet to be approved as a structurally rated CLT panel.
The specific objectives of this thesis were to: (1) determine the residual mechanical properties of salvaged lumber from Portland residential building deconstruction; (2) manufacture different experimental CLT panels using salvaged lumber, virgin lumber, and medium density fiberboard (MDF) at small-scale; and (3) examine and compare experimental CLT panels with ANSI/APA PRG 320-2018 Standards for Performance-Rated Cross-Laminated Timber. These objectives were chosen to answer our hypothesis that salvaged lumber can be used as feedstock for structural cross-laminated timber (CLT).

Salvaged lumber provided by Portland deconstruction contractors was evaluated using a Metriguard system for determining stiffness. Grading was successful on 265 boards and 96% met the minimum stiffness requirements for E3 CLT grade laminations in the major direction according to ANSI/APA PRG 320-2018.

Three different exploratory 3-ply CLT panels (all salvaged lumber, salvaged lumber outer plies with MDF core, and virgin lumber outer plies with salvaged core) were investigated. All panels were manufactured and tested in accordance with ANSI/APA PRG 320-2018. Testing results and calculations were compared to ANSI/APA PRG 320-2018 qualification criteria and benchmarks for 3-ply E3 grade CLT. All panels met reference values for E3 grade 3-ply CLT in effective flatwise bending moment resistance \((F_bS)_{\text{eff}}\), effective flatwise bending stiffness \((EI)_{\text{eff}}\), and percent wood failure \((WF\%)\).

The overall mechanical performance of manufactured panels was good, with an average \((F_bS)_{\text{eff}}\) of 60.6 \(10^6\) N-mm/m of width, \((EI)_{\text{eff}}\) of 212 \(10^{10}\) N-mm\(^2\)/m of width, \(V_s\) of 51.1 kN/m of width, and \(WF\%\) above 99%, but delamination was a problem. Percent delamination calculated from cyclic delamination test measures manufacturing process and quality, and it is possible to achieve better results if panels were made in a professional CLT manufacturing facility. Hence,
there is potential that CLT panels made with salvaged lumber are capable of meeting ANSI/APA PRG 320-2018 reference design values for 3-ply E3 grade structural CLT panels, but better manufacturing practices need to be implemented for improved delamination results and more samples need to be tested for stronger statistics.
Exploratory Study of Salvaged Lumber as Feedstock for Cross-Laminated Timber (CLT)

by
Raphael Arbelaez

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APPROVED:

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Major Professor, representing Wood Science

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Head of Department of Wood Science and Engineering

________________________________________________________________________
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.

________________________________________________________________________
Raphael Arbelaez, Author
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Dr. Laurence Schimleck aided with the writing of Chapter 2 and 3. Dr. Joseph Dahlen, from the University of Georgia, and Shawn Wood, from the City of Portland, Oregon, were also involved in the writing of Chapter 2. Dr. Arijit Sinha assisted in the writing and data interpretation of Chapter 3.
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Exploratory Study of Salvaged Lumber as Feedstock for Cross-Laminated Timber (CLT)

1 CHAPTER 1 – INTRODUCTION

Globally, humanity is increasing its consumption of materials, with countries having the highest standards of living also having the highest rates of use (Bowyer 2016). Recognition that the waste generated by our consumption has led to a focus in developed countries on recycling. Recovery rates for materials such as concrete (82%) and steel (98%) are very high (Falk and McKeever 2012) while for paper it was recently reported that a 67.2% recovery rate had been achieved in the US (AF&PA 2017). Despite these impressive figures, and a general emphasis on “recycling”, wood product recovery rates in the US of approximately 10% exist (Bowyer 2016). To understand the US market for salvaged lumber it is important to recognize the size of the US forest resource and products industry, the size and management of the US wood waste stream, the current markets available for wood waste, and the potential for high-value product manufacture, and each is outlined in this introduction.

1.1 United States in the global context of wood

In a global context, the United States has 5% of the world’s population, 7% of the of the world’s land area, 8% of the world’s forest lands (about 300 million hectares), and consumes roughly 28% of the Earth’s industrial wood products. About two-thirds, 200 million hectares, of the Nation’s forests are classified as productive and can be harvested as a source of revenue. Softwood timberlands play the largest roll in the supply of wood fiber. In 2011, 294 million cubic meters of softwoods (Oswalt and Smith 2014) were harvested to manufacture a variety of wood products, including cladding, decking, flooring, paneling, structural framing, beams, poles, furniture, cabinets and a range of pulp and paper related items (American Softwoods 2019).
Owing to having a large population, and having the highest wood consumption in the world, the United States is both a major producer and importer of wood products. While both public and private forests in the US supply much of the wood demand, the overall consumption outpaces production and supply from other forest product producing countries is necessary (Anderson 2019).

In 2005, the US consumed over 172 million tonnes of wood products, with about 45% in the form of lumber (Howe et al. 2013). New residential building construction, as well as building repairs and remodels, are main drivers for softwood lumber production in the United States accounting for over 50% of solid wood products consumption (Howard and Liang 2018). In 2006 the average new residential building construction in the US included over 33 cubic meters of framing lumber alone (Adair and McKeever 2009). In 2017, the United States milled over 57 million cubic meters of softwood lumber (Howard and Liang 2018). A majority of softwood lumber produced was to support over 1.1 million units of new housing starts in 2017 (U.S. Census Bureau and HUD 2019). However, United States softwood lumber consumption was over 90 million cubic meters in 2017, to supplement demand over 37 million cubic meters of sawn softwood was imported in 2017, 98% of which originated from Canada (Howard and Liang 2018).

Although the production and consumption of wood products support population and economic growth in the United States, problems concerning waste and its management also become matters to acknowledge. The United States faces a waste disposal problem, especially in urban areas. Most landfills are within 5 to 10 years of closing unless current facilities are expanded or new landfills are made available (Halfman 2009). In 2010, the United States generated over 63 million tons of wood waste, which equates to approximately a third of new
wood products consumed based on 2005 data (Howe et al. 2013), with nearly 27 million tons of waste deemed available for recovery (Falk and McKeever 2012). There is potential for reduced landfill pressures if better wood recovery practices are put in place, as well as more opportunities to use wood waste as a resource.

1.2 Wood waste in the United States

Having a vast system of forests and various wood product manufacturers, the United States not only produces many wood products but also generates large amounts of pre-consumer and post-consumer wood waste. Over the past 30 years an average of 130 million tonnes of wood-based products have been manufactured annually by the US (Howard and Jones 2016). During the production of wood-based products, about 76 million tonnes of wood residue are also generated, with more than 98% used by producers for fuel, pulpwood, and feedstock for other products such as particleboard and fiberboard (Smith et al. 2009). In addition to the wood residue produced by the manufacture of wood-based products, over 50 million tonnes of wood enter the US municipal and construction and demolition (C&D) waste streams each year (EPA 2018a). While pre-consumer waste from the production of wood products is commonly used by the mill, post-consumer wood waste is greatly underutilized. It is estimated that wood makes up over 10% of all waste generated in North America (Falk and McKeever 2012).

In 2010, the United States generated over 63 million tonnes of solid wood waste in the manufacture, use and disposal of solid wood products (not including wood residue produced and used by mills) (Howe et al. 2013). The principal sources of this waste are MSW and C&D waste, which generate distinctly different types of wood waste and differ in the degree of recovery and recyclability (Falk and McKeever 2012).
1.2.1 Municipal solid waste (MSW)

MSW comes from residential, commercial, institutional, and “occasional” industrial sources. It includes durable and nondurable goods, containers, packaging, food scraps, yard trimmings, storm debris, and miscellaneous inorganic waste (Falk and McKeever 2012). In 2015, 238 million tonnes of MSW were generated in the United States with nearly 26% recovered for recycling (includes composting) (EPA 2018b).

Concerning MSW, the US Environmental Protection Agency (EPA) defines “wood” to include items such as wooden furniture and cabinets, pallets and containers, scrap lumber and wooden panels. In 2015, the EPA estimated that about 14.7 million tonnes of MSW wood waste were generated (6.2% of total MSW). Further, wood from MSW accounted for 3.9% (over 2.3 million tonnes) of the 61.6 million tonnes recovered for recycling (1% of total MSW generation) and 8% of the 125 million tonnes of material landfilled (10 million tonnes of wood) (EPA 2018b).

1.2.2 Construction and demolition waste (C&D)

Although considered a single waste stream, C&D wastes originate from distinct types of activities, have different characteristics, and differ in their ease of separation, recovery and recyclability. Construction wood waste originates from the construction, repair and remodeling of residential and nonresidential structures. Demolition wood waste is produced when buildings or other structures are demolished and is often contaminated with paints, fasteners, adhesives, wall covering materials, insulation and dirt and typically contains a diverse mix of building materials (Falk and McKeever 2012).

In 2015, an estimated 497 million tonnes of C&D debris were generated in the United States; more than twice the amount generated by MSW. Debris from demolition represents more
than 90% of C&D waste generation, while construction represents less than 10% (EPA 2018a). This C&D debris also contained about 35 million tonnes of wood products (approximately 7% of total C&D waste) with only 1.3 million tonnes actually being recycled through remanufacturing (wood waste used for fuel, mulch, and compost not included) (CDRA 2019).

1.2.3 Wood waste management in the United States

The US faces the task of managing over 63 million tonnes of wood waste, annually (Howe et al. 2013). Typical management options for wood waste include recycling, energy recovery and landfilling. Wood waste in the MSW stream is often difficult to manage, separate and recover due to the variability between materials and the vast quantity of material flow. Alternatively, C&D debris is increasingly uniform and more easily separated, but contaminants are common. Additional costs associated with separation, processing, and cleaning of wood waste are common landfill issues limiting its recovery and end-of-life opportunities; hence, adding more material and pressure to landfills (CalRecycle 2019).

To address the issues surrounding waste management, several local governments around the nation have driven policy changes to help alleviate landfill pressures, promote better waste practices, and create new markets for waste wood material. Two Pacific Northwest examples are the waste bans in King County, WA, and the deconstruction ordinance in the city of Portland, OR.

1.2.3.1 King County, Washington, waste bans

In 2012, the city of Seattle, WA, passed a bill requiring C&D waste to be recycled. Seattle Municipal Code 21.3.6.089 prohibits the disposal of certain materials in construction site disposal containers and sets a schedule for banning them from disposal. This ban is part of
Seattle’s Solid Waste Plan and their Zero Waste Resolution (30990) in hopes to reach Seattle’s goal of recycling 70% of the waste produced within the city by 2025 (City of Seattle 2007).

C&D related materials account for roughly a third of all waste disposed of in Seattle (SPU 2018). To address C&D waste concerns, the ban initially covered materials such as asphalt paving, bricks and concrete. Metal, cardboard, and new construction gypsum scrap were added in 2014 while, unpainted and untreated wood was the most recent addition to the ban in 2015 under SPU Director’s Rule 405.3 Revision 4 (SPU 2018).

Wood waste recovery has risen since the inclusion of clean wood waste in Seattle’s ban. However, a majority of recovered wood is converted to mulch and animal bedding or used for “beneficial use”, which includes material not recycled or reused, but used for some other purpose, such as hog fuel for a pulp and paper mill. Though better than landfill disposal, the city of Seattle continues to seek a more aggressive approach to managing C&D wood waste, like the example of Portland deconstruction (see following section), to encourage more reuse and recycling.

1.2.3.2 Portland, Oregon, deconstruction ordinance

Portland, OR, was the first US city to implement a deconstruction ordinance in 2016 for residential structures permitting for demolition. The deconstruction ordinance requires all residential buildings, either registered historic or built before 1917, permitted for demolition to be deconstructed, unless deemed hazardous and / or dangerous. The ordinance was implemented to address landfill pressures, as well as ensure that valuable materials from demolished homes are salvaged for reuse instead of landfilled (City of Portland 2016).

More than 300 single-family homes are demolished each year, in Portland, which produce thousands of tonnes of waste. Before the ordinance, less than 10% of homes removed
were deconstructed. Now, approximately 33% of single-family dwellings applying for demolition are subject to deconstruction. Deconstruction facilitates separation and collection of quality lumber, allows quality to be maintained over time, and minimizes C&D material disposed. Benefits experienced since the adoption of this ordinance have been about 4,000 tonnes of material diverted for reuse (annually), increased job opportunities in both deconstruction and sale of recycled materials, and better discovery, removal, and disposal of contaminants like lead and asbestos (Anderson 2018; City of Portland 2016).

1.3 Markets for wood waste in the US

Reuse and/or recycling markets available for wood waste depend on issues of condition, appearance, and accessibility, and are product and use specific. Typical markets for wood waste in the United States include particleboard, animal bedding / landscaping material, pulp / paper products, composting material, energy recovery, and reuse (CalRecycle 2019).

Most pre-consumer wood waste is absorbed by wood product manufactured for either energy or other products, like paper, cardboard, particleboard, oriented strand board (OSB), and parallel strand lumber (PSL), because of material homogeneity and ease of procurement (Falk 1997; Falk and McKeever 2012; Howe et al 2013). Post-consumer wood waste, in contrast, comes from different practices and in different quality. The two main sources of post-consumer wood waste are MSW and C&D waste streams. Wood reuse and recovery for MSW is difficult due to problems associated to quantity, separation, and contamination; hence, markets for this material are few and almost completely limited to energy production. Post-consumer waste wood from C&D activities have a larger variety of markets depending on specific practices used to acquire material. Practices such as deconstruction make opportunities for the reuse of materials like flooring, and lumber available to a higher value markets. While materials from
deconstruction activities have more market opportunity and value, the impact made on the overall volume of material generated is small (Howe et al 2013).

A common problem, outside of high-end applications for the highest quality wood, is a lack of consistent markets for large volumes of waste wood (Howe et al 2013). This issue is faced by the Portland deconstruction companies that provided lumber for this research project. They have strong demand for lumber in large sizes but stud grade lumber is difficult to sell commercially. This issue is also recognized by the city of Portland who limit the number of homes for deconstruction in the fear of oversupply of salvaged lumber (Anderson 2018).

1.4 Value-added product options/potential markets

Owing to the concerns related to the underutilization of waste wood and a lack of viable markets for products manufactured from salvaged lumber, this research aims to provide a potential high value-added product option for post-consumer salvaged lumber.

High value-add is critical. While the Portland ordinance promotes good practices, like deconstruction that seeks to retain the quality of salvaged material it is also expensive to implement, hence a high-value product is required. In addition, the volume of wood provided must be consistent enough to meet the demands of a customer.

Product options for waste wood have been considered in the past and a conference on this topic was held in Madison, WI, in 1996. The potential material and product types discussed were recycled lumber and timber, wood fiber-plastic composites, and wood/inorganic-bonded products (Falk 1997). Additionally, the Wood Handbook states that a variety of wood sources, including the waste stream, are appropriate for use in wood-based composites (Ross 2010). Mass timber wood composites, like dowel-laminated timber (DLT), nail-laminated timber (NLT), glue-laminated timber (glulam), and cross-laminated timber (CLT), could potentially be a new
market for salvaged lumber. An example of this is the Kendeba Building for Innovative Sustainable Design at the Georgia Institute of Technology campus. The building construction used NLT for the decking which was composed of locally salvaged wood and southern yellow pine (Hummel 2018).

Considering mass timber product options, CLT is the most attractive for this study. It uses large volumes of wood, can utilize variable amounts of salvaged lumber, i.e. it could be used in a panel that is 100% recycled or could be used for core or outside layers only (depending on supply) and lumber quality of different grades can be used in different ply’s providing an option for wood of lower quality. It also has the potential to appeal to the architectural community as products manufactured from recycled materials can be utilized to accrue points in green building systems, provides an opportunity for Carbon offsets, and aesthetically provides an attractive option.

1.5 Cross-laminated timber (CLT)

CLT is a relatively new structural building product that originated in Germany and Austria in the early 1990’s. It is a large-scale, prefabricated, solid engineered wood panel consisting of several layers of kiln-dried lumber stacked in alternating directions, bonded with structural adhesives, and pressed to form a solid, straight, rectangular panel for roof, floor, or wall applications (Karacabeyli and Douglas 2013).

While the majority of CLT manufacture remains in Europe, new facilities have established in North America, Asia and Australia owing to increased popularity and associated benefits with use. Likewise, CLT as a building material is being explored in Australia, Japan, Canada, New Zealand, and the US (Muszynski et al 2017).
Lightweight yet very strong, with superior acoustic, fire, seismic, and thermal performance, CLT is also fast and easy to install, generating almost no waste onsite. CLT offers design flexibility, and low environmental impacts. For that reason, CLT is proving to be a highly advantageous alternative to conventional building materials like concrete, masonry or steel, especially in multi-family, and commercial construction.

With the growing popularity of building with CLT in the early 2000’s, building construction and code authorities in North America developed the CLT Handbook (Canadian edition in 2011 and US edition in 2013) and the Standard for Performance-Rated CLT (ANSI / APA PRG 320-2018) that provides CLT-related information and guidance (Karacabeyli and Douglas 2013; ANSI/APA 2018). Collectively the documents provide a peer-reviewed information resource that can be used for the design and construction of CLT structures. It was developed cooperatively by FPInnovations, American Wood Council, APA, Forestry Innovation Investment, WoodWorks, and the USDA Forest Products Laboratory. Information in the handbook provides an “alternative” path in building codes and design standards to assist CLT construction. PRG320 is a performance-rated product standard that prescribes requirements and tests for the qualification and quality control of structural CLT manufacturing in North America.

With standards established, the first certified CLT panel produced in the US was supplied by DR Johnson Lumber Co., in Riddle, OR. In 2016, around the same time as DR Johnson Lumber Co., Smartlam in Columbia Falls, MT, also started manufacturing certified structural CLT panels. DR Johnson Lumber Co. and Smartlam are currently the only two certified structural CLT manufacturers in the U.S. International Beams, in Dothan, AL, Katerra, in Spokane, WA, and Vaagen Timbers, in Colville, WA, are new structural CLT facilities in progress of entering the market and are expected to be in production by 2020. Furthermore,
LignaCLT and Smartlam are proposing the construction of new CLT facilities in Maine (Parajuli et al 2018).

The APA Engineered Wood Products standards committee first addressed the concern of product standards for North American CLT manufacturing in 2010. Their objective was simple, to develop a standard for CLT for the US and Canada. The process of developing a CLT standard in North America started in 2010 and first put in place in 2012. Since then, the standard has seen multiple revisions with the most frequent done in 2018 to address concerns with fire.

The PRG 320 performance standard is a prescriptive one that specifies material requirements for CLT and methods used for certification. Material requirements, such as species and grade of lumber used in laminations and types of adhesives usable for bond laminations, are clearly stated in the standard. In addition to pre-manufacturing requirements, the standard also refers to specific testing criteria for determining if manufactured CLT meets grade requirements.

PRG 320-2018 specifies seven grades of CLT panels depending on material used for manufacture. The seven CLT grades consisted of four for CLT made with machine graded lumber (E1, E2, E3, and E4) and three for that made with visually graded lumber (V1, V2, and V3). Grade groups are determined by lumber strength characteristics, which are also closely correlated to wood species. Regardless of grade, PRG 320 requires that all prequalified panels have a minimum of No.2 visual grade lumber used in the major direction and No.3 lumber used in the minor direction layers.

While PRG 320 contains specific information for meeting certain CLT grades, it also provides information and protocols for custom CLT lay-ups to be designed, tested, and certified. Custom lay-ups may include ones using alternative raw material stock, like structural composite
lumber (SCL), or different lay-ups, like double outer layers or unbalanced layups (ANSI/APA 2018).

Because PRG 320 allows for CLT product customization, it is theoretically possible to make a certified CLT panel out of a wide range of wood-based products; so long it meets minimum strength requirements. The idea of customization has been explored by researchers around the globe using different species, wood products, as well as waste wood.

Studies done by Kramer et al (2013), Wang et al (2014), Gong et al (2015), Aicher et al (2016), and Liao et al (2017) all look at using different hardwood species in hybrid softwood-hardwood CLT panels. Kramer et al (2013) and Wang et al (2014), both found that poplar (Populus spp.) could be used in the cross-layers of CLT panels without compromising mechanical properties. Gong et al (2015) evaluated the potential of using aspen (Populus tremuloides) and birch (Betula alleghaniensis) in the cross layer of hybrid CLT panes and had promising results showing that both species could significantly improve planar shear performance of CLT products in timber construction. Likewise, the study done by Aicher et al (2016) showed that the use of low-grade hardwoods, like beech (Fagus sylvatica), in cross-layers of CLT can be extremely promising with improved load capacity behavior. Liao et al (2017) found similar results with fast-grown small diameter Eucalyptus (Eucalyptus urophylla x Eucalyptus grandis), stating that mechanical properties of the manufactured eucalyptus CLT were equivalent to those of commercially available softwood CLT.

Similar to the exploratory studies of hybrid CLT using alternative species, research done by Wang et al (2015) and Davids et al (2017) have examined alternative wood products for layers of CLT panels. Wang et al (2015) explored the possibility of using laminated-strand lumber (LSL) in the core and / or outer layers of CLT panels made with 2-by-4 lodgepole pine
and showed that using LSL (core or outer layers) improved mechanical properties. Davids et al (2017) also explored the use of LSL in hybrid Spruce-Pine-Fir (South) (SPFs) CLT panels and found that LSL in the core of CLT panels increases bending stress failure through mitigation of rolling shear.

A more recent study by Rose et al (2018) explored the concept of using waste timber (or “secondary timber”) as feedstock for CLT. Motivation for this study related to the large volume of waste timber the construction industry generates, which has residual quality and value, but is lost in conventional waste management strategies. The researchers in this study believe that if cross-laminated secondary timber (CLST) can replace CLT, steel, and concrete in some applications, this creates upcycling to displace materials of greater environmental impact as well as a value-added opportunity for waste timber. Results from this study showed no significant difference between the structural performance of CLST and regular CLT. Furthermore, finite element modeling (FEM) of CLST suggested that the defects present in secondary timber have only a small effect on CLST panel stiffness in compression and bending. Conclusions made by Rose et al (2018) state that secondary timber can be used for CLT production but questions concerning quality and quantity of material, grading, cost, and scale need addressing.

Given this, preliminary research to investigate the feasibility of using salvaged lumber for CLT manufacture was performed. Specific objectives of this study were:

1. To determine the residual mechanical properties of salvaged lumber from Portland residential building deconstruction;

2. To manufacture different experimental CLT panels using salvaged lumber, virgin lumber, and medium density fiberboard (MDF) at small-scale; and

1.6 References


CHAPTER 2 – EVALUATION OF LUMBER FROM DECONSTRUCTED PORTLAND RESIDENTIAL BUILDINGS

CHAPTER 2 – EVALUATION OF LUMBER FROM DECONSTRUCTED PORTLAND RESIDENTIAL BUILDINGS

2.1 Abstract

Portland, Oregon was the first US city to implement a deconstruction ordinance in 2016. Although salvaged lumber from deconstructed dwellings can have high demand, the market for small-sized lumber is near saturation. New applications for this material are required for market development, industry diversification, and the possible expansion of the deconstruction ordinance. Its use in mass timber is an option, but presently no wood property information exists for lumber from deconstructed dwellings, inhibiting its use for structural purposes. Density and dynamic MOE (E) of 265, 38 mm x 89 mm (2 x 4) pieces of salvaged Douglas-fir (Pseudotsuga menziesii) lumber were determined using a Metriguard Model 340 E-Computer. Additional data collected included sample dimensions, weight, and visual appearance. Over 50% of samples had a calculated stiffness comparable to the highest structural design grade for Coastal Douglas-fir lumber. The presence of knots and damage, present in 66% and 59% of boards respectively, would likely downgrade boards despite acceptable stiffness. Results show that 96% of samples were sufficiently stiff to meet minimum requirements for the manufacture of E3 grade cross-laminated timber (CLT) panels, and considering defects, this material is suitable for manufacturing CLT. Provision of wood property information for salvaged lumber is critical for market expansion, and this work represents the first characterization of lumber from deconstructed Portland, OR, dwellings.

Keywords: Cross-laminated timber (CLT), deconstruction, density, Douglas-fir, salvaged lumber, stiffness.
2.2 Introduction

The United States generates approximately 70 million tonnes of solid wood waste annually with municipal solid waste and construction and demolition waste being the principal sources. Residues from primary manufacturing facilities represent a sizable proportion but are already heavily used, and excluding what is burnt for heat, already salvaged, or unusable, approximately 29 million tons still have the potential to be recovered (Falk and McKeever 2012). Despite the value that this resource represents, retrieval is uncommon, with the level of recycling for domestic lumber and other structural materials being in the range of 10-11% (Bowyer 2016). The recovery lags well behind the 67.2% recovery rate reported for paper (AF&PA 2017) and that reported for steel (98%) and concrete (82%) (Falk and McKeever 2012) because recovery and reuse is not trivial compared with the aforementioned products unless the intention is to simply burn the biomass.

With a global trend of increasing material consumption (Bowyer 2016), it is imperative that society increases efforts to recycle/reuse materials in general, although for lumber specifically, recovery rates of approximately 10% indicate a grossly underutilized resource. As noted by Bowyer (2016), efforts exist to recover a greater proportion of the wood available. Common approaches include increasing deconstruction frequency (rather than demolition), building component reuse, and recovery of discarded wood.

Demolition is effectively the destruction, breakdown, or removal of a structure at the end of its design life (Rahman 2019). It is generally the complete elimination of all building parts, at a specific location and time, for new construction or development (Thomsen et al 2011). Methods used to demolish residential structures typically involve heavy machinery (excavators and bulldozers) which destroy potentially salvageable material, thus preventing reuse (Nunes et al
Conversely, deconstruction is “the process of disassembling a physical structure to its components in reverse order to that used during construction with minimum damage so that they maintain their original physical properties and structural integrity” (Diyamandoglu and Fortuna 2015). It presents a viable alternative to demolition after the reduction in disposal costs (landfill), income generated from the sale of salvaged materials, and potential to create employment are considered (Diyamandoglu and Fortuna 2015; Nunes et al 2019). Recognizing the benefits of deconstruction, the City of Portland, OR, adopted an ordinance in October 2016 which aimed to increase the frequency of building deconstruction (Wood 2016).

In Portland, the number of “single-dwelling structures” that are demolished annually is approximately 300, and of these less than 10% are deconstructed (Wood 2015). Under the existing resolution, “projects seeking a demolition permit for a one- or two-family structure (house or duplex) will be required to fully deconstruct that structure if: 1. The structure was built in 1916 or earlier; or 2. The structure is a designated historic resource” (Wood 2015). Approximately 34% of demolished structures per year in Portland would qualify for these two categories (Wood 2015). Provisions for exemptions will include structures that are determined to pose an immediate safety hazard and structures that are determined to be unsuitable for deconstruction/salvage (e.g., rot, mold, or fire damaged) (Wood 2015). The Bureau of Planning and Sustainability have provided grants to incentivize involvement in deconstruction projects and also provided training and certification opportunities; to this end, there are now 13 certified deconstruction contractors working in the city. The impacts of the ordinance have been immediate; in a recent status report (dated March 12, 2018), 318 demolition permits for the period October 31, 2016 to October 30, 2017, were approved. Of these, 80 were covered by the deconstruction ordinance (Anderson 2018).
Questions exist regarding the structural quality of lumber salvaged from deconstructed buildings, and few reports exist providing such information. The provision of quality data is critical as without it salvaged wood cannot be utilized for structural applications. Falk et al (1999a) collected lumber of various sizes from the Twin Cities Army Ammunition Plant in Arden Hills, MN, when it was dismantled in 1995. They focused on engineering properties of 2 × 10 lumber (38 x 236 mm). Five hundred pieces were visually graded on-site and indicated that 28.4% of the 500 pieces were Select Structural, 8.4% No. 1, 19.4% No. 2, 15.6% No. 3 and 28.2% economy (<No. 3), but it was estimated that up to 30% of the lumber was downgraded as a result of damage (mainly splits) during deconstruction. A subsample of 100 randomly selected pieces were shipped to the USDA Forest Service Forest Products laboratory (Madison, WI) and destructively tested. Measured stiffness was similar to that of lumber produced commercially at the time of the publication; however, lumber strength was less than expected. It was thought that chemical contamination related to the use of the building (production of magazines for explosives) may have weakened the lumber; however, chemical analysis of wood from the building was inconclusive. An interesting finding was the species used in construction since it was believed that Douglas fir (Pseudotsuga menziesii) was used. An examination by a wood anatomist revealed that 53% was Douglas fir, 25% Hemlock-Fir, and 22% southern pine. In a related study of lumber from the Fort Ord US Army Military Reservation in Marina, CA, it was again observed that damage affected the grade assigned in over one third of the lumber (Falk et al 1999b). Careful deconstruction practices were emphasized to increase the yield of high grades of lumber.

It can be deduced from the age of the buildings being deconstructed in Portland that the lumber was cut from “old-growth” trees and has the potential to be of exceptional quality;
however, no reports exist that characterize the wood from this important resource. Therefore, this study aimed to characterize wood sourced from deconstructed buildings in the Portland metro area in hopes of supporting market development, industry diversification, and the possible expansion of the deconstruction ordinance. The research is part of a larger study examining the utilization of reclaimed dimension lumber for the manufacture of cross-laminated timber (CLT) panels. The study was motivated by the need to find new high-value markets for salvaged lumber as concerns exist that supply of dimensional lumber now available owing to the deconstruction ordinance exceeds what the market can absorb (Anderson 2018).

2.3 Materials and methods

2.3.1 Salvaged lumber

A total of 483 rough-cut 38mm x 89 mm (2 × 4) pieces of salvaged lumber (892.31 linear meter total length) were supplied by three deconstruction contractors in the Portland metro area. Contractors were asked to provide material that had minimal metal, paint and no hazardous contaminants. Rough-cut lumber was selected because it represents lumber typical of what is being salvaged from dwellings in Portland built before 1916. Lumber were separated by length, as the target CLT panel size was 1.14m by 2.28m. Two groups were identified: <2.3m for use in the minor direction of CLT panels, and ≥2.3m for the major direction. There were 267 boards in the <2.3m group and 216 boards in the ≥2.3m group. In addition to length, sample width and thickness were also measured.

2.3.2 Salvaged lumber assessment

A Metriguard Model 340 E-Computer (Metriguard Inc. Pullman, WA) was used to grade the lumber for wood stiffness measurements. Grading was attempted on all 483 boards; however, 218 boards were too short to be graded. The Metriguard Model 340 E-Computer is a portable test
system for calculating the dynamic MOE \((E)\) of a board by measuring its natural frequency (Hz) induced by tapping the center of the board with a small rubber mallet in the center of the span. It consists of two tripods, one with a calibrated load-cell and the other with a knife-edge, and an interface unit. Samples were placed flatwise on the knife and load cell, with a 25 mm overhang on each side. Weight and five frequency measurements were collected for each board. The average frequency was determined and used to calculate an E-value for each tested board. If the five readings were not recorded after 10 taps (when the board was too short to record a vibration frequency), the sample was set aside and testing continued. Data recorded for each sample (dimensions, weight and average frequency) was used to calculate \(E\), in pounds per square inch (psi), according to (Metriguard 2011):

\[
E = \left(\frac{f_n^2 \cdot W \cdot L^3}{K \cdot b \cdot h^3}\right)
\]

where \(E\) is the MOE (psi), \(f_n\) is the undamped natural frequency (Hz), \(W\) is sample weight in pounds, \(L\) is span length in inches (total length minus two inches of overhang), \(K\) is the adjustment of constant used to accommodate the units used and the support conditions (equal to 79.37), \(b\) is width of test sample in inches (horizontal distance), and \(h\) is the thickness of test sample in inches (vertical distance).

When the samples were tested by the Metriguard, notes were also taken on the visual appearance including splits/checks, knots, biodegradation, surface damage, holes, wane, pitch/resin pockets, warp and uneven surface. Defects either were marked as present or absent. Brief descriptions of identified defects follow:

1. Splits and/or checks: appeared to be natural cracks formed by wood shrink/swelling, or cracks possibly formed during deconstruction and material handling.

3. Biodegradation: evidence of any rot and/or insect attack.

4. Holes: only holes arising from wiring and construction.

5. Wane: included any bark, or tree exterior present on boards.

6. Pitch and/or resin pockets: the presence of surface resin or resin-filled cavities.

7. Warp: twisted or distorted boards.

8. Uneven surface: boards with a face that was milled unevenly.

Mold, nail holes and other small defects were disregarded when visually inspecting the lumber.

Thirty MC readings were randomly collected from the graded salvage lumber. Average MC was then calculated and used to adjust $E$ to 15% MC using the following formula (ASTM 2007):

$$S_2 = S_1 \cdot \left( \frac{B_1 - (B_2 \cdot M_2)}{B_1 - (B_2 \cdot M_1)} \right)$$

where $S_2$ is the adjusted $E$ to 15% moisture content, $S_1$ is the calculated elasticity (psi) at the average moisture content, $B_1$ is a constant (equal to 1.857), $B_2$ is a constant (equal to 0.0237), $M_1$ is the average moisture content (%) when tested, and $M_2$ is the target moisture content of 15%.

After grading boards and correcting for moisture content, $E$ values were converted from psi to gigapascals (GPa).

2.4 Results and discussion

Dimensional measurements and density were recorded for all 483 rough-cut pieces of salvage lumber. A total of 265 boards (all 216 boards in the ≥2.3m-group and 49 of the 267 boards in the <2.3m-group) were graded using the Metriguard system, and subsequently, visually inspected for defects. A summary of the groups, attempts at grading, and salvage boards graded are shown in Table 1.
2.4.1 Visual Examination

Examination of the end-grain (or cross-sectional surface) of the reclaimed lumber indicated that it was of high quality and consistent with lumber sourced from old-growth forests (Fig 1). Many pieces were quarter-sawn, had ring boundaries that were close to linear, and had exceptionally tight growth rings; all these indicate that the lumber was milled from very old, slow-growing trees. The average ring count per centimeter of these boards was eight rings and ranged from 2 to 19 rings. Of these 48 randomly selected boards, 17 had 10 or more rings per centimeter. Wood species identification was also performed on these boards using hand lens, and all were Douglas fir. As a consequence, all salvage lumber in this study were compared to published characteristics, standards, and test values for Douglas fir.

A summary of the visual defects observed, for the 265 graded samples, is provided in Table 2. Knots were the most common defect observed occurring in 66% of samples. For some pieces of lumber, knot size was extreme, covering over 75% of wide-face width and containing large cracks. Knots of this magnitude are rare to find in today’s commercial structural lumber because modern silvicultural practices focus on straight, clear wood through self-pruning (due to high planting density and competition), genetic selection (for branch quantity, size, and angle), and short rotation-age (restricts the size/age a branch can reach). Checks and/or splits, damage and holes were also common with 59% of all samples showing some sign of physical degradation. No samples showed signs of warp.

Evidence of resin and biodegradation were found in 11% and 5% of all samples, respectively. In a living tree, resin has a protective role, repelling insects and fungi, and covering wounds, eg from physical damage or fire. For Douglas-fir, resin “bleed” over time is common on non-kiln dried pieces and can either appear as dark spots on the ends of fresh cut lumber or beads
of resin on the surface. Resin pockets were less frequent but are a common feature in Douglas-fir and arise from damage caused by the Douglas-fir beetle (*Dendroctonus pseudotsugae*) (Belluschi 1965). Agents of biodegradation were wood-decay fungi and insects. The two wood-decay fungi found were likely brown trunk rot and red ring rot (sometimes called white spec) (Hollingsworth 2018). Even though brown trunk rot (*Laricifomes officinalis*) is a common problem in Douglas fir, producing decay that appears dark brown and with a checked surface, the one sample found with this decay only showed minimal damage. Red ring rot (*Porodaedalea pini*) occurred in seven samples and is common in older Douglas fir. Damage observed from red ring rot appeared moderate to advanced with a honeycomb appearance and white, spindle-shaped pockets of decay (Hollingsworth 2018).

Four boards showed evidence of insect attack consistent with Cerambycidae and ambrosia beetles. Cerambycidae are long-horned beetles and round-headed wood borers. Species in this family that reside in the Pacific Northwest generally infect only standing timber or green lumber, leaving large tunnels that can extend the length of boards. Ambrosia wood boring beetles (Scolytinae subfamily) make much smaller tunnels when compared to Cerambycidae. Ambrosia beetles get their name from the symbiotic relationship they have with the “ambrosia fungus.” Ambrosia fungi is a mold/stain fungus, ie usually beetle specific, originating from small holes located on the exoskeleton of beetles. In exchange for habitat, transportation, and food, beetles and larvae use this fungus as nourishment since they do not consume wood directly (Six 2003). When the beetle and fungus find a host, beetle tunnels are typically lined with black stain and/or contain distinctive black rings owing to the symbiotic fungal relationship; however, they were observed for only one board. Interestingly, this board also showed other beetle attack, brown trunk rot, physical damage, and resin; however, it is sufficiently stiff for use in CLT.
The cross-sectional dimensions of the lumber was quite variable (Fig 1). Since 1924, the American Lumber Standard Committee have developed voluntary product standards published under procedures established by the US Department of Commerce. In the early 1970s, the publishing of Voluntary Product Standard PS 20 and development of the first National Grading Rule for Softwood Dimensional Lumber resulted in uniform lumber sizes, grade names and grading provisions. Standard sizes for finished dry nominal 2 × 4 lumber, that is currently milled and distributed is 38.0 mm by 89.0 mm actual size. Permitted variation in lumber dimension is 0.79 mm under in 20% of pieces and 0.79 mm over in all pieces for No.2 and better grades, and 1.59 mm over or under on opposing faces in 20% of the pieces for Studs, Utility and No.3 grades (WWPA 1991).

2.4.2 Nondestructive Testing

As boards used in this study were acquired from houses older than the first established grading rules, uniform dimensions were not expected. Both the average thickness and width of all 483 boards were greater than current grading standards for 2 × 4 lumber: 43.0 mm and 90.6 mm, respectively (Table 3). Differences between the largest and smallest measurement for thickness and width were 15.8 mm and 16.3 mm, respectively (Fig 2). Like standard lumber sizes, the differences in dimensions among boards also exceeded the permitted variation in lumber described by current grading rules.

Taking note of the width and thickness variations in salvage lumber is important because, compared to lumber presently cut, this will be an issue for CLT manufacturers. All lumber would need to be planed to a consistent thickness and be within tolerances, before to gluing for meeting performance standards. Thickness consistency is required for manufacturing, but processing to achieve consistent width may also be required; however, it is not absolutely necessary and may
depend on the manufacturer. The desired end product may also important. Glulam, eg manufactured under the CaReWood process described in Risse et al (2017), would require lamellae cross-sectional dimensions to be carefully controlled.

Douglas fir is native to the Pacific Northwest of the United States and Canada and has been the most common softwood species used for construction in the Portland area because of its strength, durability, and workability. The reported average density for this species is 510 kg/m³ (Kretschmann 2010). The density of all 483 boards (Fig 3) was calculated using measured dimensions and the weight provided by the Metriguard. Although the coefficient of variation for density was higher than that of thickness and width, 11% as opposed to 6% and 3%, respectively, the average density of 530.7 kg/m³ is comparable to published values (Table 3).

2.4.3 Grading

Samples were compared to design standards only after adjusting to 15% MC (as required). The average MC for the 30 random measurements equaled 11% (SD = 2%) and was used for MC adjustment. Of the 265 samples that could be graded using the Metriguard, 72% had an $E$-value of 11 GPa or greater, the design value for No.2 Douglas Fir-Larch. Disregarding visual defects, Table 4 shows percentage of boards in each visual grading category based on National Design Standards stiffness values (AWC 2015). Since the samples tested are part of a larger study, E-values were also compared to the allowable stress design (ASD) reference values for laminations used in manufacturing CLT (ANSI/APA 2018). The larger study aimed for CLT layup grade of E3, which required laminations in the major direction to have an E-value no less than 8.3 GPa, with 96% of the 265 samples meeting the minimum requirements (Table 5). Distribution of E-values are shown in Fig 9. Summary statistics for salvage lumber graded with Metriguard are shown in Table 6.
Although many boards had high stiffness, application of individual boards in structures will inevitably be determined by defects and condition, hence limiting the material available for structural use. CLT presents an opportunity to loosen structural and defect requirements by randomizing imperfections and working as a composite system either using all salvage lumber or a combination of virgin and salvage lumber. Still, any material intended for structural applications, whether working alone or in a system, should be extensively tested and understood, in accordance to design standards, before being widely accepted and used. In their recent study, Rose et al (2018) noted the importance of this information and highlighted the need for further research in to better understand salvaged (“secondary”) lumber properties and variability.

The provision of wood property information for salvaged lumber is critical for the expansion of markets, and future research possibilities should examine different non-destructive, as well as destructive tests, for determining static MOE and MOR. In practice, it will also be important to assess the MC of recovered lumber to identify any pieces having high MC and in need of drying before reuse. A portable moisture meter would suffice for this purpose. In addition, because this population study only focused on rough-cut salvage lumber from the Portland-metro area, similar studies should be administered in different cities, for different species, on rough-cut and planed lumber, and on boards from various waste streams.

2.5 Conclusion

Dynamic MOE of 265 rough-cut 38 mm x 89 mm (2 x 4) pieces of salvaged lumber were determined using a Metriguard Model 340 E-Computer. Over 50% of samples had a calculated stiffness equal to or greater than, the highest structural design grade (Select Structural, 13.1 GPa) for Coastal Douglas-fir lumber. The presence of large knots and physical damage, present in 66% and 59% of boards, respectively, would likely downgrade boards, despite their acceptable
MOE. In all, 96% of the 265 salvaged Douglas-fir boards graded using a Metriguard Model 340 E-Computer tested with a stiffness equal to, or greater than the minimum stiffness required for use in the major direction of a grade E3 CLT panel (≥8.3 GPa). Provision of wood property information for salvaged lumber is critical for market expansion and this work represents the first characterization of lumber from deconstructed Portland, OR dwellings.

2.6 Acknowledgments

We thank the Tallwood Design Institute at Oregon State University for financial support, and also NW Deconstruction Specialists/Reclaim NW, The ReGuilding Center, and Good Wood Deconstruction & Salvage for provision of reclaimed lumber.

2.7 References


Wood S (2015) City of Portland Resolution No. 37190 (17 February 2016), Portland, OR.

Wood S (2016) City of Portland Ordinance No.187876 (06 July 2016), Portland, OR.

WWPA (1991) Western lumber grading rules. Western Wood Products Association, Portland, OR.
Figure 1. Picture of end-grain for a random sample of salvaged lumber.

Figure 2. Thickness and width distributions (mm) for 483 pieces of salvaged lumber.
Figure 3. Frequency distribution for the density (kg/m³) of 483 salvaged lumber pieces.

Figure 4. Frequency distribution of Modulus of Elasticity (GPa) for 265 pieces of salvaged lumber (Metriguard).
Table 1. Summary of salvage lumber groups and grading using Metriguard.

<table>
<thead>
<tr>
<th>Group</th>
<th># Boards</th>
<th>Attempted</th>
<th>Graded</th>
<th>Not Graded</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 2.3m</td>
<td>267</td>
<td>267</td>
<td>49</td>
<td>218</td>
</tr>
<tr>
<td>≥ 2.3m</td>
<td>216</td>
<td>216</td>
<td>216</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>483</td>
<td>483</td>
<td>265</td>
<td>218</td>
</tr>
</tbody>
</table>

Table 2. List of defects identified and their relative abundance (265 samples).

<table>
<thead>
<tr>
<th>Visual Defect</th>
<th>% of tested</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Major Defects</td>
<td>9%</td>
</tr>
<tr>
<td>Checks/Splits</td>
<td>34%</td>
</tr>
<tr>
<td>Knots</td>
<td>66%</td>
</tr>
<tr>
<td>Biodegradation</td>
<td>5%</td>
</tr>
<tr>
<td>Damage</td>
<td>28%</td>
</tr>
<tr>
<td>Holes</td>
<td>11%</td>
</tr>
<tr>
<td>Wane</td>
<td>7%</td>
</tr>
<tr>
<td>Pitch</td>
<td>11%</td>
</tr>
<tr>
<td>Warp</td>
<td>0%</td>
</tr>
<tr>
<td>Uneven Surface</td>
<td>3%</td>
</tr>
</tbody>
</table>

Table 3. Salvage lumber summary statistics (483 samples).

<table>
<thead>
<tr>
<th></th>
<th>Average</th>
<th>Max</th>
<th>Min</th>
<th>sd</th>
<th>CoV (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness (mm)</td>
<td>43.02</td>
<td>51.56</td>
<td>35.81</td>
<td>2.71</td>
<td>6%</td>
</tr>
<tr>
<td>Width (mm)</td>
<td>90.55</td>
<td>100.58</td>
<td>84.33</td>
<td>2.38</td>
<td>3%</td>
</tr>
<tr>
<td>Density (kg/m³)</td>
<td>530.70</td>
<td>718.41</td>
<td>338.13</td>
<td>59.96</td>
<td>11%</td>
</tr>
</tbody>
</table>
Table 4. Percent of boards in visual grade categories according to National Design Standards (NDS) for Douglas fir – larch structural lumber grading (265 samples).

<table>
<thead>
<tr>
<th>Grade</th>
<th>E-value (GPa)</th>
<th>% of tested</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS</td>
<td>13.1</td>
<td>51%</td>
</tr>
<tr>
<td>No. 1 &amp; Btr</td>
<td>12.4</td>
<td>5%</td>
</tr>
<tr>
<td>No. 1</td>
<td>11.7</td>
<td>8%</td>
</tr>
<tr>
<td>No. 2</td>
<td>11.0</td>
<td>10%</td>
</tr>
<tr>
<td>Construction</td>
<td>10.3</td>
<td>9%</td>
</tr>
<tr>
<td>No. 3/Stud/Stand</td>
<td>9.7</td>
<td>6%</td>
</tr>
<tr>
<td>Utility</td>
<td>9.0</td>
<td>5%</td>
</tr>
<tr>
<td>Below grade</td>
<td>&lt;9.0</td>
<td>8%</td>
</tr>
</tbody>
</table>

Table 5. Percent of boards in grade categories according to required Allowable Stress Design (ASD) elasticity values for CLT in the United States (265 samples).

<table>
<thead>
<tr>
<th>Grade</th>
<th>E-value (GPa)</th>
<th>% of tested</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1</td>
<td>11.7</td>
<td>18%</td>
</tr>
<tr>
<td>E2</td>
<td>10.3</td>
<td>9%</td>
</tr>
<tr>
<td>E3</td>
<td>8.3</td>
<td>9%</td>
</tr>
<tr>
<td>E4</td>
<td>13.4</td>
<td>45%</td>
</tr>
<tr>
<td>V1</td>
<td>11.0</td>
<td>10%</td>
</tr>
<tr>
<td>V2/V3</td>
<td>9.7</td>
<td>6%</td>
</tr>
<tr>
<td>Below Grade</td>
<td>&lt;8.3</td>
<td>3%</td>
</tr>
</tbody>
</table>

Table 6. Summary statistics for salvage lumber Modulus of Elasticity (GPa).

<table>
<thead>
<tr>
<th>Metriguard Grading Statistics</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg</td>
<td>13.6 GPa</td>
</tr>
<tr>
<td>Max</td>
<td>25.6 GPa</td>
</tr>
<tr>
<td>Min</td>
<td>2.9 GPa</td>
</tr>
<tr>
<td>sd</td>
<td>3.5 GPa</td>
</tr>
<tr>
<td>CoV (%)</td>
<td>26%</td>
</tr>
</tbody>
</table>
CHAPTER 3 – SALVAGED LUMBER FOR CROSS-LAMINATED TIMBER (CLT)

PANELS: MANUFACTURING AND TESTING

3 CHAPTER 3 – SALVAGED LUMBER FOR CROSS-LAMINATED TIMBER (CLT) PANELS: MANUFACTURING AND TESTING

3.1 Abstract.

Portland, OR, was the first US city to implement a deconstruction ordinance in 2016. While 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 like cross-laminated timber (CLT) could be a new market for this material, but presently there is minimal information qualifying the performance of CLT 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 plies and test results were used to calculate the effective flatwise bending moment resistance \((F_{bS})_{\text{eff}}\), effective flatwise bending stiffness \((E_{I})_{\text{eff}}\), effective shear stiffness in flatwise bending \((G_{A})_{\text{eff}}\), flatwise shear resistance \(V_s\), percent wood failure \((WF\%)\), and percent delamination \((\text{Delamination}\%)\). Results were compared to E3 grade 3-ply CLT panels made in the US, and indicated that salvaged lumber could be used as feedstock for CLT panels in core layers or all layers. All panel layups passed benchmarks for \((F_{bS})_{\text{eff}}\) and \((E_{I})_{\text{eff}}\) benchmarks with values greater than PRG 320. Panels having salvaged lumber in the core layer also met \(V_s\) benchmarks. Further, all panels passed examination for \(WF\%)\, but struggled to meet delamination requirements. There might be possibilities 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 is needed to verify findings.

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

3.2 Introduction

About 70 million tonnes of municipal solid waste (MSW) and construction and demolition (C&D) wood debris is generated annually in the US, with over 40% still available for recovery (Falk and McKeever 2012). While wood has a multitude of potential uses, about 60% of the wood used in the US 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). Post-service life recovery for this material ranges between 10-11% and lags far behind the rates for steel (98%) and concrete (82%) (Bowyer 2016; 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, Oregon was the first city in the US 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 non-profit entities that have established retail outlets for materials. Market demand is strongly driven by reuse and the do-it-yourself (DIY) 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 to 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 that the In-Grade bending strength, but bending stiffness was about 10 percent 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 over 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 does 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, 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 CLT 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. 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.
3.3 Materials and methods

3.3.1 Materials for CLT manufacture

A total of 265 Douglas-fir (*Pseudotsuga menziesii*) 38 mm x 89 mm (2 x 4) boards of salvaged lumber, 84 pieces of Douglas fir 38 mm x 98 mm x 2.4 m No. 2 virgin lumber, and three TRUPAN VESTA NAF MDF panels (1.2 m x 2.4 m x 25.4 mm), which were made with 100% recycled/recovered wood content, were used to manufacture CLT panels. Salvaged lumber was 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) was used for the manufacture of CLT panels. LOCTITE HB X452 PURBOND has an assembly time of 45 minutes and a curing/pressing time of 112 minutes. 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 minutes prior to adhesive application. We used a spread rate of 180 g/m², 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 co-authors 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 (5) 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.

3.3.2 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 that day received a fresh face within
24 hours 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 1a). 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. 1b) before all surfaces to be adhered were misted with primer solution 15 minutes prior to applying adhesive (Fig. 1c). Once misted, and after 15 minutes, 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. 1d). 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 3 layers (Fig. 1e).

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

3.3.3 Sample extraction and testing

After manufacturing, the panels were stored indoors at 20°C and 36% relative humidity for at least 24 hours. Panels were then cut to their final dimensions (1.1 m by 2.3 m by 3 plys) and the pre-panel 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).
3.3.3.1 Bending samples

Long-span and short-span bending samples measured 2.3 m long by 0.3 m wide by 3 plies deep and 0.54 m long by 0.3 m wide by 3 plies deep, respectively. Testing procedures for bending samples followed ASTM D198-15 for flatwise bending. Bending tests were conducted using a universal testing machine (UTM) and MTS actuator. Long-span tests used third point loading while 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 continually collected.

3.3.3.2 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. 4a). Before testing, block shear samples were conditioned for over two weeks in a standards room at 20°C and 65% relative humidity to provide a sample moisture content of 12% at the time of testing. Tests were conducted on a UTM equipped with a 10 kN load cell (Fig. 4b). Each test was conducted at a rate of 0.9 mm/min and loaded until failure. After completing tests, red safranin was used to stain the transparent PUR bond line to calculate percent wood failure. Once stained, transparent 5 mm x 5 mm grid paper was used to quantify the percent wood and adhesive failure per sample (red meaning wood failure and clear meaning adhesive) (Fig. 4c).

3.3.3.3 Cyclic delamination samples

Cyclic delamination followed procedures stated in 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 three plies deep (Fig. 5a). Like block shear
samples, cyclic delamination samples were also conditioned to 12% moisture content before testing. The procedure used for the cyclic delamination test consists of three parts; a vacuum (at 510 to 640 mm Hg for 30 minutes)/pressure soak cycle (517±34 KPa for 120 minutes) 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 hours), and then inspection of delamination (Fig. 5b and 5c).

3.3.4 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 \((Vs)\), percent wood failure \((WF\%)\), and percent delamination \((\text{Delamination\%})\) in the major direction. Long-span bending test data was 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.

3.3.4.1 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 max load and span of samples for calculating the max 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 max moment can be calculated to find \((F_bS)_{\text{eff}}\) (Karacabeyli and Douglas 2013).

The equations used appeared as follows:

\[
F_b' S_{\text{eff}} \geq M_b \therefore M_{\text{max}} = \frac{P_{\text{max}}l}{6} \div b = (F_bS)_{\text{eff}}
\]

where \(P_{\text{max}}\) is the max load at failure, \(l\) is span, and \(b\) is the width of the sample.

3.3.4.2 Effective flatwise bending stiffness \((EI)_{\text{eff}}\)

Deflection and load data, recorded by the actuator, were used to determine effective flatwise-bending stiffness. The equation utilized 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):

\[
(EI)_{\text{eff}} = \frac{K a}{24} (3l^2 - 4a^2) \div b
\]

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 max load, and \(b\) is the width of the sample.

3.3.4.3 Effective shear stiffness in flatwise bending \((GA)_{\text{eff}}\)

Equations available in the CLT Handbook were used for calculating the effective shear stiffness in flatwise bending of samples. Since the equation for the effective shear stiffness in flatwise bending accounts for the properties of individual layers in a CLT 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 \(G_i = E/(16\times10)\) 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):
\[(GA)_{eff} = \frac{a^2}{\frac{h_1}{2G_1b_1} + \frac{h_2}{G_2b_2} + \frac{h_3}{2G_3b_3}}\]

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

### 3.3.4.4 Flatwise shear resistance \((V_s)\)

Short-span bending test data was used for calculating flatwise shear resistance. The formula used was the following:

\[V_s = \frac{VQ}{Ib} \times l\]

where \(V\) is the max 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.

### 3.3.4.5 Percent wood failure \((WF\%)\)

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

\[WF\% = 1 - \left(\frac{\text{Grid Area}_{not\ red}}{\text{Grid Area}_{total}} \times 100\%\right)\]

### 3.3.4.6 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 due to 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:

\[
\text{Bondline Delamination (\%)} = \frac{\text{Bondline Length}_{\text{delamination}}}{\text{Bondline Length}_{\text{Total}}} \times 100\%
\]

3.4 Results

Nine exploratory 3-ply CLT panels (dimensions were 1.14 m by 2.28 m by three plies) were manufactured using salvaged lumber from Portland, Oregon 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.

3.4.1 Results summary

Table 1 summarizes the average values for each criterion considered by panel type. Also listed in Table 1 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 criterion for E3 grade 3-ply CLT panels as per ANSI/APA PGR 320-2018. Not considering the delamination values, for both 100%SL as well as VL-SLcore, the properties were above the benchmark values for grade E3. SL-MDFcore did not meet the shear stiffness as well as shear resistance benchmark. This was expected since shear flow is essentially though the core material and with MDF being a weaker material in shear than solid lumber, yielded a weaker panel in shear. With advances and changes in adhesive technologies for this particular application, it is possible to reduce the % Delamination in the future.
3.4.2 Bending tests

For the long-span samples, failure type, maximum load at failure, and deflection varied amongst samples. Fig. 6a presents the 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 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 panels 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, while 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 while the others failed in rolling shear of the middle layer. Max 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 max 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). The load-deflection characteristic is presented in Fig. 6B. 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 averaged substantially lower deflections at maximum load (Fig. 6b).

3.4.3 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 max load range between 6.0 kN and 9.4 kN. Samples from SL-MDFcore panels resisted the least average max load, at 6.8 kN, with a range between 4.8 kN and 9.0 kN.

3.4.4 Cyclic delamination test

Data recorded during cyclic delamination tests were associated with changes in mass due to water adsorption/desorption and samples (assumed conditioned moisture content 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. 100%SL panel samples had the second highest average moisture uptake (103%) and samples from SL-MDFcore panels had the lowest (102%). After 15 hours 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.

3.4.5 Calculated properties

Calculated values were used for comparing to the E3 Grade, 3-ply CLT panel, ASD reference design values for CLT in the US, 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.

3.4.5.1 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), while 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 to 85.4 \(10^6\) N-mm/m of width), and highest between samples taken from 100%SL panels (43.7 to 82.9 \(10^6\) N-mm/m of width).

The \((F_{bS})_{eff}\) design values published in ANSI/APA PRG 320-2018 for E3 grade 3-ply CLT panels manufactured in the US is 12.5 \(10^6\) N-mm/m of width. For a direct comparison to 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 \((F_{bS})_{eff}\).

3.4.5.2 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-mm²/m of width (100%SL), 223 \(10^{10}\) N-mm²/m of width (SL-MDFcore) and 204 \(10^{10}\) N-mm²/m of width (VL-SLcore). Individual \((EI)_{eff}\) values ranged from 178 \(10^{10}\) N-mm²/m of width (a sample from VL-SLcore panel), to 248 \(10^{10}\) N-mm²/m of width, for a sample from a SL-MDFcore panel.

ANSI/APA PRG 320-2018 published \((EI)_{eff}\) benchmark for E3 grade 3-ply CLT panels manufactured in the US is 76.3 \(10^{10}\) N-mm²/m of width. All samples had a calculated \((EI)_{eff}\) at least twice that of the ANSI/APA PRG 320-2018 benchmark.
3.4.5.3 Effective shear stiffness in flatwise bending \((GA)_{\text{eff}}\)

Samples from 100%SL panels and samples VL-SLcore panels had similar \((GA)_{\text{eff}}\) values, while samples from SL-MDFcore panels were much lower. The calculated average \((GA)_{\text{eff}}\) 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 \((GA)_{\text{eff}}\) values and values between panel types did not overlap. The ANSI/APA PRG 320-2018 \((GA)_{\text{eff}}\) benchmark for E3 grade 3-ply CLT panels manufactured in the US is 5.11 \(10^6\) N/m of width and only SL-MDFcore panel samples failed to meet \((GA)_{\text{eff}}\) benchmark values.

3.4.5.4 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 range in values of samples from 100%SL panels (52.76 to 63.13 kN/m of width) and VL-SLcore panels (53.39 to 66.50 kN/m of width) were similar. Samples from SL-MDFcore panels, in contrast, had the lowest average \(V_s\) (35.95 kN/m of width), as well as greatest variability between samples ranging from 27.25 kN/m of width, the lowest value amongst all calculations, to 48.75 kN/m of width.

The \(V_s\) design value set by ANSI/APA PRG 320-2018 for 3-ply E3 grade CLT manufactured in the US is 16.20 kN/m of width. Like for \((FS)_{\text{eff}}\), the \(V_s\) design values in PRG 320 needed to be adjusted for comparison to reference test values. Published design values for \(V_s\) were multiplied by 3.1 to obtain reference values, as per ANSI/APA PRG 320. Once 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 a SL-MDFcore panel, having a $V_s$ of 27.25 kN/m of width.

3.4.5.5 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%. 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.

3.4.5.6 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). In 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 to 23.4%) and VL-SLcore panels (0 to 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 criteria only one 100%SL met PRG delamination requirements.

3.5 Discussion

Portland, Oregon’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 CLT manufactured using salvaged lumber feedstock to determine if its performance was sufficient for it to be a viable product option. CLT panels were manufactured and tested in accordance with ANSI/APA PRG 320-2018 and results
compared to values published (after adjustments) in performance standards for E3 grade 3-ply CLT panels.

Along with salvaged lumber, the potential of manufacturing structurally rated CLT with an MDF core was also explored. MDF was selected because it’s 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 CLT 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 material in outer layers since 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, while VL-SLcore samples did not. Consistent with Rose et al. (2018), this supports findings that localized defects, like large knots, in salvaged lumber used in the outer layer of CTL panels can play a role in performance. While 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 to lumber. Compared to a similar study done investigating the use of low-value lumber from small-diameter timber for CLT production, the average max 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, while 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 to 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 owing to 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 even though samples from SL-MDFcore panels weren’t as strong in bending as other samples (having a lower effective flatwise bending moment resistance \((F_{bS})_{\text{eff}}\)), it was stiffer on average (having a higher effective flatwise bending stiffness \((E_l)_{\text{eff}}\)). The equations provided by the CLT Handbook for calculating \((G_A)_{\text{eff}}\) took properties of individual pieces of lumber into consideration. While 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 \((G_A)_{\text{eff}}\). Furthermore, since the calculation for \((G_A)_{\text{eff}}\) solely used material properties, SL-MDFcore panels would never achieve a sufficiently high enough \((G_A)_{\text{eff}}\), because of the lower elasticity properties of the MDF material used.

Results and observations indicate that salvaged lumber could be used as feedstock for CLT 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 ANSI/APA PRG 320-2018 E3 grade CLT. Further, 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. Further, 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 CLT manufacturing facility and/or if automation of manufacturing processes were available. Despite, the positive results, more research is needed on CLT 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 CLT 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 done 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 (CNC) machine should be used to cut samples.

3.6 Conclusions

The goal of this study was to manufacture and test custom experimental CLT layups containing salvaged lumber. All experimental CLT layups were three 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 ANSI/APA PRG 320-2018: Standard for Performance-Rated Cross-Laminated Timber. Panel benchmarks and qualifications criteria considered were effective flatwise bending moment resistance \((F_{bS})_{eff}\), effective flatwise
bending stiffness \((EI)_{\text{eff}}\), effective shear stiffness in flatwise bending \((GA)_{\text{eff}}\), flatwise shear resistance \((V_s)\), percent wood failure \((WF\%)\), and percent delamination \((\text{Delamination}\%)\).

Our results indicate that salvaged lumber could be used as feedstock for CLT 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 CLT manufacturing facility and/or if automation of manufacturing processes were available.

3.7 Acknowledgements

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3.8 References


American National Standards Institute, Tacoma, WA.


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

Figure 3. (a) Long-span third-point bending test setup and (b) Short-span center-point bending test setup.
Figure 4. (a) Block shear “stair-step” samples based on 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 AITC Test T110-2007, (b) Pressure cylinder used for vacuum/pressure soak cycle, and (c) Oven used for rapid drying cycle (AITC 2007).
Figure 6. (a) Example long-span bending load-deflection curves for a sample of each panel type and (b) Example short-span bending load-deflection curves for a sample of each panel type.
Table 1. Average results for each experimental panel layup compared to ANSI/APA PRG 320-2018 E3 grade 3-ply panel after taking converting design values to test values for \((F_bS)_{eff}\) and \(V_s\) as per ANSI/APA PRG

<table>
<thead>
<tr>
<th>Panel Layup</th>
<th>(F_bS) (N-mm/m of width) and CoV%</th>
<th>(E_l) (N-mm²/m of width) and CoV%</th>
<th>(G_A) (N/m of width) and CoV%</th>
<th>(V_s) (kN/m of width) and CoV%</th>
<th>WF% and CoV%</th>
<th>Delamination% and CoV%</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-ply E3 Grade CLT panel</td>
<td>2.62E+07</td>
<td>7.63E+11</td>
<td>5.11E+06</td>
<td>51.02</td>
<td>&gt;80.0%</td>
<td>&lt;5%</td>
</tr>
<tr>
<td>100% Salvaged Lumber</td>
<td>6.41E+07</td>
<td>2.08E+12</td>
<td>1.12E+07</td>
<td>2%</td>
<td>99.0%</td>
<td>3.0%</td>
</tr>
<tr>
<td>Virgin w/ Salvaged core</td>
<td>8.04E+07</td>
<td>2.04E+12</td>
<td>1.05E+07</td>
<td>3%</td>
<td>99.9%</td>
<td>0.0%</td>
</tr>
<tr>
<td>Salvaged w/ MDF core</td>
<td>3.74E+07</td>
<td>2.23E+12</td>
<td>2.11E+06</td>
<td>1%</td>
<td>35.9%</td>
<td>21%</td>
</tr>
</tbody>
</table>
CHAPTER 4 – CONCLUSIONS

Markets exist for salvaged lumber, but more end-of-life options are necessary for wood waste recovery efforts to advance. High-value added markets are desirable (to offset recovery costs) with structural applications being an attractive option. Cross-laminated timber (CLT) is a large structural wood composite that could potentially be made using salvaged lumber, allowing for a greater role in structural applications as well as expanding market opportunities. This thesis evaluated the mechanical properties of salvaged lumber from Portland residential building deconstruction for the manufacture of structurally rated CLT panels in a series of custom 3-ply panel layups. The performance of manufactured CLT panels were also evaluated against performance standards to determine if panels made with salvaged lumber could meet the pre-plant qualification criteria in ANSI/APA PRG 320-2018.

In Chapter 2, 483 rough-cut pieces of salvaged lumber from Portland, OR, residential building deconstruction practices were evaluated to determine their potential to be used for the manufacture of E3 grade CLT panels. The salvaged lumber was selected because of accessibility and the recognition by the City of Portland that new applications for salvaged material are required to support its deconstruction ordinance, as well as provide opportunities of market expansion. The E3 grade of CLT panel was chosen because it uses machine rated lumber, had the lowest design requirements, and allowed the greatest lumber species flexibility. Data recorded for each board included dimensions, density, weight, and visual defects. Visual inspection showed that the two most common defects are large knots and physical damage (from natural checking/splitting and/or deconstruction practices). Attempts were made at measuring residual stiffness of all boards using a Metriguard machine grading system, and grading was successful on 265 boards. Of the boards graded, 96% had a stiffness greater than 8.3 GPa, the minimum
requirement for E3 grade laminations in the major direction. Overall, although the salvaged material had defects, the overall quality was high, reflecting good deconstruction practices. However, multiple salvaged lumber boards that met CLT stiffness requirements also had defects that would not meet current structural lumber grading standards. Salvaged boards were still used because the negative effects associated to defects can be minimized in a composite like CLT.

Salvaged lumber that successfully met the minimum stiffness requirements were used to make 3-ply CLT panels in Chapter 3. Three experimental panel layups were chosen and each had three replicates giving nine panels. The three CLT panel layups tested were 100% salvaged lumber, salvaged lumber outer plys with MDF core, and virgin lumber outer plys with salvaged lumber core.

These exploratory panel layups were selected mostly because they used salvaged lumber in differing amounts and recycling potential (for example using an MDF core provided an option for wood that could no longer be used for lumber). Panels made with virgin lumber outer plys were about 23% recycled content, while the other layup types consist of 100% recycled material. Selecting to make and test panels with MDF core also explored the possibility of using lower-value composites in CLT, which could further expand possibilities for wood waste. Although results for MDF core panels were not to structural benchmarks, possibilities for appearance grade panels could be a future market opportunity.

Panels were manufactured and tested as per ANSI/APA PRG 320-2018, and measured 2.3 m by 1.1 m. Specific tests administered were long-span bending in major direction, short-span bending in major direction, block shear test, and cyclic delamination test. Reference design values considered for qualification were the effective flatwise bending moment resistance \((F_{bS})_{eff}\), effective flatwise bending stiffness \((EI)_{eff}\), effective shear stiffness in flatwise bending
\((GA)_{\text{eff}}\), flatwise shear resistance \((V_s)\), percent wood failure \((WF\%)\), and percent delamination \((\text{Delamination}\%)\).

All test samples exceeded the \((F_{bS})_{\text{eff}}\) and \((EI)_{\text{eff}}\) values published in ANSI/APA PRG 320-2018 for 3-ply E3 grade panels, and also met the percent wood failure benchmark criteria. While all panels made with a MDF core failed to meet benchmarks for \((GA)_{\text{eff}}\) and \(V_s\), perhaps a CLT panel with a composite core, having slightly better shear properties than the MDF used in this study, could meet all benchmarks. All panels made with 100% salvaged material and panels with virgin outer plies showed good mechanical properties, but delamination was an issue. Only one of the nine panels met all benchmarks and qualification criteria, and it was a panel made with 100% salvaged lumber. All panels made with 100% salvaged lumber, as well panels having virgin outer plies passed all benchmarks if delamination was set aside. The percent delamination measured after the cyclic delamination test is an indicator of manufacturing processes and quality more so than a mechanical property. If panels containing salvaged lumber are manufactured in an industrial setting, and with automation, there is possibility for the issue of delamination to be resolved. This shows that it is possible to use salvaged lumber as feedstock for structurally preforming CLT, given the right precautions are taken and the right technology is available. More research needs to be done for verification, but these results have valuable meaning for the advancement of product options for salvaged lumber.

Aside from grading, the two main barriers to using salvaged lumber for CLT manufacturing is the presence of metal and lumber dimensional variability. Although salvaged lumber was requested metal-free scanning with a metal detector located numerous pieces of metal (mostly nails and screws) that had to be removed. After removing metal and grading lumber, dimensional variability between boards also required addressing (sizes were not
consistent as lumber was cut before standards were developed). Making salvaged lumber straight and consistent thickness required considerable processing and time, which could be the greatest barrier for using salvaged lumber for CLT.

The future of salvaged wood in mass timber products like CLT is promising but will depend on addressing highlighted issues. Methods and standards for grading need to be developed for salvaged lumber to play a role in structural applications. In addition, issues with lumber variability need to be addressed for salvaged lumber to become feedstock for mass timber products. CLT manufacturing facilities will not invest the time and capital trying to make salvaged lumber consistent and homogenous for their operations. This might present an opportunity for an organization to facilitate the process of taking salvage lumber from waste to resource, becoming somewhat of a “middle-man” for the industry.

Even with the addition of a material processing entity to facilitate salvaged material flow into a CLT facility, the utilization of this resource will ultimately be determined by cost. At its current state, salvaged lumber has an average price of $3.30 USD per linear meter and this price would have to be reduced significantly to compete successfully with virgin lumber, or there will have to be a premium paid for CLT manufactured from salvaged lumber which may be possible with building certification systems assigning value to recycled materials being used in new construction.
5  CHAPTER 5 – BIBLIOGRAPHY


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