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Editorial

Cross laminated timber and the larger family of massive timber products have been receiving unprecedented attention for wood products. Interest from the architecture and engineering communities has been very strong. Several years ago, Wood Design Focus published an issue dedicated to CLT research. The issue was largely provided by researchers and collaborators with FPInnovations, who were one of the driving forces to bring CLT from Europe to Canada. Ever since that issue, interest in CLT has grown and several large-scale buildings have now been built in Canada and the United States. Many scientists and researchers have been involved with CLT research.

Recently a Mass Timber Workshop was held at the Forest Products Laboratory in Madison, WI where over 120 engineers, architects, researchers and academics met to discuss current CLT efforts and develop a roadmap for future research and collaboration. Next March22-24, a Mass Timber Conference sponsored by the Forest Business Network will be held in Portland, Oregon (www.masstimberconference.com).

This issue of Wood Design Focus is a continuation of the previous CLT issue. However this time, the issue focused on the research and development efforts of cross-laminated timber in the United States. Topics include a summary of research efforts on massive timber, a market analysis of CLT perceptions among architects, modeling the properties of yellow-poplar for use in hardwood CLTs, and a method for examining the rolling shear properties of CLTs. We hope you enjoy this issue. At the end of each article, author contact information is provided if you would like further information.

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CLT Research: Available and Accessible to North American Building Designers

Lisa Podesto PE, Scott Breneman PhD SE PE

In 2010, cross laminated timber (CLT) took US designers by storm when architect Andrew Waugh toured the US sharing the amazing success of what was, at that time, the tallest modern timber structure in the world. A nine-story building constructed almost entirely of CLT seemed out of reach for designers in the US; yet here we are five years later with approved codes and standards inclusive of CLT construction up to six stories prescriptively and perhaps more using the performance path. Cross laminated timber and other mass timber technologies have captured the interest of designers, industry and governments alike. The result of all this interest is the need for lots of research and the need has not gone unanswered.

An interesting aspect of CLT research to date is not only that there has been so much in such a short period of time but also that it has been uncharacteristically well organized and distributed; not always the norm in the world of research. The motivation for such a swift and organized effort stems from a perfect storm of factors surrounding this innovative structural system:

- Market need: Designers are looking for a low-carbon building material to address drastic reduction goals for atmospheric carbon emissions.
- Available resources: The North American public forest inventories are increasing in age and density, leading to increased potential for fire and disease. CLT and other mass timber products offer high value markets for low-value small diameter logs yielded from forest restoration projects.
- Social/economic motivation: Rural economies that rely on the forest products industry have been in steady decline. High-value products such as CLT provide opportunities to stimulate job growth in non-urban communities.

Keywords: Cross Laminated Timber, North America, Research, Fire, Structural Properties, Seismic

In 2013, FPInnovations and the Binational Softwood Lumber Council in association with the USDA Forest Products Laboratory, American Wood Council, APA – The Engineered Wood Association and WoodWorks published the US Edition of the *CLT Handbook* (Karacabeyli and Douglas 2013), making relevant European and North American research accessible to US designers. By deciphering important results, offering conclusions, and identifying where further study was needed, that document has provided an important foundation for the research that has taken place since and is yet to come.

Several sources of funding, including the Softwood Lumber Board, Binational Softwood Lumber Council, Natural Resources Canada, the USDA Wood Innovation Grant program and the Canadian NEWBuildS Network, are enabling research efforts to move forward for many new wood building systems, including CLT. These programs have the benefit of being well-coordinated and also having an outreach component. This prevents research institutions across North America from being islands of knowledge, allowing each research project to build upon the others and offering an opportunity for early input from the manufacturing and design industries. For example, the NEWBuildS program has a single steering committee reviewing all of the funding proposals from over 13 participating research institutions. Their website provides access to abstracts and papers on all CLT-themed research in a single location, making it easy to determine what's being done without insider knowledge about which universities are working on what. Another site, the Wood Education and Resource Center hosted by the US Forest Service, contains similar information for USDA grant funded projects. Further improving access to research, the wood industry -- funded by the Binational Softwood Lumber Council and Forestry Innovations Investment -- is pursuing a single database to house information on completed and in-progress research on CLT and other mass timber systems. The databased will be made available via the rethink Wood website (www.rethinkwood.com).

In addition to widespread accessibility, CLT research has also been largely application based. Organizations like WoodWorks that are focused on assisting designers with non-residential and multi-residential projects are providing a mechanism for identifying the needs of architects and engineers and putting them at the forefront of research discussions. Structural and fire summits were held in November 2014 in association with WoodWorks' *Toward Taller Wood Buildings Symposium* in Chicago, serving as a kind of research charrette for this purpose. Bridging the gap between data and design has been a strength of the organization, which has helped support the rapid growth of CLT manufacturing and the greater mass timber industry. The purpose of this article is to highlight research efforts recently completed and underway that address pressing questions related to the design and construction of CLT, thus allowing continued pursuit of this product as a mainstream building system.

Since the *CLT Handbook's* release, a code definition for CLT has been established through the code cycle process and now appears in the 2015 *International Building Code* (IBC). The definition recognizes the *APA/ ANSI PRG 320 Standard for Performance-Rated Cross-Laminated Timber* (ANSI/APA 2012), and specifically calls out opportunities for its use in prescriptive Type IV construction. The American Wood Council also recently published the *2015 National Design Specification® (NDS®) for Wood Construction* with specific design standards for CLT (AWC 2015). While research and the Handbook played a role in these achievements, the conclusions presented in the Handbook and subsequent inquiries from the design community highlight the need for further study, most notably in the areas of fire performance and seismic/structural analysis.

Fire Performance

Fire performance, and specifically exposed fire resistance, may be one of the most asked about areas in terms of additional research information—but, in reality, suffers more from misperception than lack of research data. The predictability of wood's char rate has been well established for decades and has also been recognized for years in US building codes and standards. However, the use of existing code provisions has not been commonplace in modern commercial construction; therefore, jurisdictional comfortability with an expanded use of those provisions for the purpose of CLT design has presented a challenge. The 2015 NDS includes a char calculation procedure to provide calculated fire resistance of up to two hours. It expands on the design examples in the fire chapter of the US CLT Handbook by allowing for laminations of varying thicknesses. Further study and additional full-scale panel tests continue to be done, not necessarily to prove legitimacy of the CLT char methodology but to support expansion of its applicability. Areas of expansion include new assembly configurations (in pursuit at the Advanced Composite Lab and the University of Maine), exploring performance under non-standard fires and developing performance prediction tools (as was done at Carleton University under the NEWBuildS program).

The Fire Research Team at the USDA Forest Products Laboratory is studying the fire resistance properties of CLT panels in order to improve their marketability for low to midrise construction. The goal is to find a panel layup that maximizes the hourly fire rating so structural panels can be used in a larger variety of situations. Recent studies on 25 CLT specimens have investigated how features such as the grade of wood, layout of individual boards, adhesives and protective membranes can be optimized to reduce the charring rate and increase the hourly rating of the panel. This research is being performed in conjunction with Virginia Tech, Clemson University and North Carolina State University.

It is commonly asked why there are not Underwriters Laboratories (UL) or equivalent tested assemblies available for CLT and this area is often suggested for research. The truth is that the calculated method offers more flexibility to designers than a series of UL assemblies and provides more precision with regard to the panel thickness needed to accommodate fire-resistive requirements. When structural strength and fire resistance are so intertwined, a prescriptive method for determining fire resistance cannot offer material efficiency. A comparison of the ASTM E 119 fire tested CLT performance and the predicted performance using the calculated method demonstrates the reliability of char calculations for CLT. Such a comparison can be done by independent designers but is also shown in graphical form with tests done prior to 2013 in the fire chapter of the US Edition of the *CLT Handbook* (Karacabeyli and Douglas 2013).

The impressive ability of CLT to meet two and three hours of fire resistance with and without gypsum protection seems to be overshadowed by concerns about its combustibility. The increase of wood volume raises necessary questions about the additional potential for structural contribution to combustion and what it means for fire safety. Full-scale fire tests completed by FPInnovations and funded by Natural Resources Canada and others are intended to help address this issue. In association with a 13-story mass timber demonstration project (12 stories of CLT over one story of concrete) in Quebec, the provincial government there funded full-scale CLT fire tests to prove CLT's equivalence to 2-hour-rated non-combustible construction.

- One series of full-scale compartment tests compared the performance of light-gauge steel, light-frame wood and CLT. Tests included a three-story encapsulated CLT apartment simulation that ran for three hours. Details of this study are described in a previous WDF article (Dagenais 2015). Results of the apartment simulation show the effectiveness of encapsulation in significantly delaying CLT's potential contribution to fire growth and proved that the structure can withstand complete burnout. The summary study went so far as to state, "Results show that, with encapsulation, the three test apartments constructed using wood structural elements provided the level of fire performance that meets the NBC intent statement assigned to the noncombustible construction requirement in limiting the involvement of the structural elements in fire and in limiting the contribution of the structural elements to the growth and spread of fire." (Su and Lougheed 2014, p.105).
- Another test focused on a 25.5-ft CLT stair/elevator shaft (exposed on the inside face with two layers of gypsum protection on the fire side) and studied the smoke propagation and leakage as well as its structural stability as a fire exit. The test ran for two hours and showed no sign of smoke or heat penetration into the shaft.

One area highlighted by the Handbook as needing more study was detailing for penetrations and concealed spaces. Research recently completed by FPInnovations and funded by Natural Resources Canada/The Canadian Forest Service evaluated the ability of selected fire stops and sealing joints in CLT assemblies, both for panel joints and around through-penetrations to prevent the passage of hot gasses and limit heat transfer. Results showed that products commercially available for use in light-frame and concrete construction are also feasible for CLT applications. (Dagenais 2014)

Structural and Seismic Performance

There has been a proliferation of industry and academic research initiatives to build out the body of knowledge on CLT structural performance in US applications.

Some have pertained to standards and testing methods suitable to North America, such as the investigation of testing protocols for evaluation of in-plane shear strength of CLT panels (Gagnon et al. 2014). These and other efforts have led to the new *Acceptance Criteria For Cross -Laminated Timber Panels For Use As Components In Floor and Roof Decks* (AC455) from the ICC Evaluation Services. This product evaluation standard is generally compatible with the ANSI/APA PRG 320 qualification requirements with a notable addition of testing procedures for evaluating the in-plane strength of CLT panels. Having acceptance criteria for CLT panels allows manufacturers to pursue directed testing culminating in an Evaluation Service Report (ESR). ESR reports are helpful in gaining jurisdictional approval for new materials, further assisting designers. Current North American CLT manufacturers are promising ESRs in the near future.

Research into connection technology for North American CLT has included static and cyclical testing of self-tapping screws for CLT-to-CLT and CLT-to-wood beams performed at the University of British Columbia in Vancouver, Canada (Hossain 2015 and Ashtari 2014). In addition to connection behavior, Ashtari et al. looked at the behavior of a horizontal CLT floor system as a diaphragm of a lateral force-resisting system.

Using CLT components in lateral (wind or seismic) force-resisting systems is an area of considerable ongoing research. A much anticipated project is the *Development of Seismic Performance Factors for Cross Laminated Timber* with principal investigator John van de Lindt of Colorado State University. This project will follow the Federal Emergency Management Agency (FEMA) P-695 process, which is currently underway, to rigorously quantify seismic performance factors (R, Ω_o and C_d) for a type of CLT shear wall system for use following seismic design procedures of ASCE 7. This comprehensive study was preceded by a site- and building-specific FEMA P-695-like study to estimate whether a seismic Response Modification Factor of $R = 4.5$ met the performance objectives of the candidate design (Pei 2013). To date, CLT shear wall systems for seismic resistance have been designed using conservative seismic performance factors or using advanced performance-based seismic design procedures. The completion of this research will be a significant step toward easier design of CLT shear wall systems for seismic resistance and eventual inclusion of CLT in the seismic structural design standards used throughout the US.

Another research project evaluating CLT walls for seismic resistance is a Network for Earthquake Engineering Simulation (NEES)/National Science Foundation (NSF) project investigating seismic-resistant tall wood buildings for the Pacific Northwest (Pei 2014a). This multiuniversity project is executing an inclusive process to develop seismic performance goals, as well as a variety of potential high-performance/low-damage seismic force-resisting systems. Since the 2014 publication on this project, the research team has progressed to running a series of experimental tests of CLT rocking walls at Washington State University. Additional research is being performed on the design of CLT rocking walls at Clemson (Gu et al 2014) and the University of Alabama.

For those wanting to know more about the history of CLT seismic research, the 2014 *Journal of Structural Engineering* forum article entitled *Cross-Laminated Timber for Seismic Regions: Progress and Challenges for Research and Implementation* is a very good resource (Pei 2014b).

Additional Research

In addition to expanding knowledge of CLT as it is currently manufactured and used, other research is exploring different ways to manufacture CLT by using different source material, for example, such as southern pine (Hindman and Bouldin, 2014) and hybrid poplar (Kramer et al., 2013), or the inclusion of voids within the panels (Montgomery et al. 2014). These new opportunities are intended to allow for greater utilization of lower-value small diameter timber stocks that are available across the country.

The U.S. Tall Wood Building Prize Competition, sponsored by the Softwood Lumber Board, USDA and Binational Softwood Lumber Council, is also providing support for and helping drive research into practical applications of tall wood buildings across the U.S.

WoodWorks is working to expand military, public, and private markets for wood construction by studying the blast performance of CLT wall systems with funding from a USDA Wood Innovation Grant. Karagozian & Case, an internationally recognized protective design consultant, with support from the Advanced Composites Lab at the University of Maine and several other research and government institutions, is collaborating with WoodWorks to test the dynamic performance of the material and propose a design methodology based on the results of this testing.

Prioritizing the research needs for CLT was the focus of a recent Mass Timber Workshop hosted by the USDA Forest Products Laboratory. With a large diversified attendance of designers, researchers, and industry, outcomes are expected to influence upcoming funding allocations and help to ensure that the future of CLT research meets market needs.

CONCLUSION

As low carbon alternatives to other building materials, mass timber products are poised to revolutionize the landscape of the built environment. They're also helping to bolster rural economies, because stronger markets for wood products provide an incentive for public and private landowners to invest in the long-term sustainability of North American forests.

With tremendous interest in the potential of CLT in particular, prompt attention has been given to its inclusion in building codes and standards, with the awareness that a great deal of research is still underway. In addition to the research described in this paper, the depth and breadth of research on CLT is spreading to embrace other mass timber systems, including the development of mechanically-laminated products such as dowel- and nail-laminated timber, and the expanded use of glue-laminated timber.

WEB RESOURCES

http://www.na.fs.fed.us/werc/

http://newbuildscanada.ca/

http://www.bcfii.ca/tools-resources/market-research/

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Cross Laminated Timber in the U.S.: Potential Adopter Perceptions

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ABSTRACT

Cross-laminated timber (CLT) is an innovative structural system based on the use of large-format, multi-layered panels made from solid wood boards glued together alternating the direction of their fibers. This cross-laminated configuration improves rigidity, dimensional stability, and mechanical properties of the panels, which can be used for many applications such as walls, floors, and roofs. Since its introduction, more than 20 years ago, CLT has been successful in Europe, and has made inroads in the Australian and Canadian markets. In the United States the adoption of the system is still in its early stages. In order to better evaluate the market potential for CLT in the U.S., this project aimed at assessing the level of awareness, perceptions and willingness to adopt the system by U.S. architecture professionals. To achieve these objectives, interviews with CLT experts were conducted, followed by a nation-wide survey of U.S. architecture firms. Results show that potential adopters identified the use of wood, a natural and renewable material, as the main advantage of CLT. Commonly cited perceived disadvantages of CLT were its acoustic and vibration performance. Notably, results show that the level of awareness about CLT is low among U.S. architects. Building Code compatibility, availability of the product in the domestic market, and cost were mentioned as the main barriers to the implementation of the system in the U.S. Architects are likely to adopt CLT for their near -future projects, especially for multi-family, commercial, and recreational buildings. Importantly, willingness to adopt CLT was positively correlated to the level of awareness with the system. Results show that diffusion of knowledge about CLT will be essential for the successful introduction of this new structural system into the U.S. market.

Keywords: *Cross-laminated timber, CLT, massive timber, engineered wood products, sustainable buildings, wood-based construction.*

INTRODUCTION

One of the latest innovations in the area of wood construction has been the development of cross-laminated timber (CLT). CLT is a building system based on large-format solid timber panels. These panels are configured similarly to plywood, with boards that are glued side by side in a single layer and then glued to other similarly constructed layers placed at right angles. This configuration improves rigidity, stability, and mechanical properties. Because of their construction, CLT panels can take up forces in all directions, allowing them to be used as walls, roofs or slab elements (Lattke and Lehmann 2007; Lehmann 2012). Typically, a cross section of a CLT panel has between three and seven (odd numbers to achieve a balanced construction) glued layers. The final dimensions of the panels are typically between 2 and 9 feet wide, and up to 79 feet long (Crespell and Gagnon 2011). During the manufacturing of the panels, lumber is visually graded or machine stress-rated and kiln dried before boards are finger jointed and glued together using structural adhesives. After panels have been pressed and machine-surfaced, openings for windows, door and service channels, connections and ducts are cut using CNC (Computer Numerical Controlled) routers. Elements are then packed and sent to the construction site, ready to be put into place with cranes (Crespell and Gagnon 2011). CLT panels are connected to each other using metal connectors such as steel angles and metal splines. Screws are used to attach these connectors to the panels (Crespell and Gagnon 2011, Karacabeyli and Douglas 2013). CLT can be used in a wide range of applications, such as single- and multi-family residences, barns, power line towers, churches, bridges, and mid- and high-rise buildings. This versatility has added visibility and reputation to the system (Ceccotti et al. 2010, Sanders 2011).

The use of CLT has become a popular and successful method of construction in Europe since its introduction, and has been recently introduced into the Canadian and Australian markets, with more than 50 buildings erected in the former using this building system (Crespell 2015). The U.S. market for CLT is still in its embryonic stage. So far, only a handful of small projects have been built with CLT, most of them with imported panels. The market development in the U.S. has been hindered in part due to the lack of manufacturing facilities in the country. As of December 2015, there were only three CLT manufacturers in the United States, and only one with APA/ANSI certification.

Extensive research has been carried out to evaluate CLT performance as a structural system, such as mechanical properties, fire and thermal performance, and seismic behavior (Harris et al. 2013, Karacabeyli and Douglas 2013, Kuilen et al. 2011). However, market research has been scarce. To addresses this lack of information, this study aimed at assessing the market potential for CLT in the United States.

METHODOLOGY

To achieve the objective of this research, the project was carried out in two stages: (1) a set of interviews with CLT experts, and (2) a nationwide survey of U.S. architecture firms. A more detailed description of the research approach follows.

Interviews With CLT Experts

With the purpose of gaining understanding about the awareness, perceptions, and willingness to adopt CLT by the U.S. construction industry, a series of interviews with CLT experts were conducted during summer of 2013. Interviewees were chosen based on their experience and knowledge about CLT-related topics. Names and contact information were obtained from publications available online and recommendation by academic experts. The list of experts included professionals from the academic, manufacturing, architecture, and industry promotion communities. Participants were located in the U.S., Canada, and Austria. Interviewees were initially contacted via email to invite them to participate in the study and set up a convenient day and time for the interview.

A list of ten questions was prepared. Questions covered the following categories: demographic information; benefits and barriers for the implementation of CLT in the U.S.; awareness of CLT in the architecture community; perceptions about CLT and willingness to adopt CLT by the U.S. construction industry. Interviews were conducted over the phone and were recorded (with the participant's consent) for analysis and future reference. All interviews were fully transcribed, coded, and analyzed using established qualitative research methods.

Survey of U.S. Architecture Firms

The goal of this part of the study was to assess the market potential and barriers to adoption of Cross-Laminated Timber (CLT) in the United States through a survey of potential adopters in the architecture community. Results from the first part of the study (see previous section) provided the main input for this phase of the research. Specifically, a web-based survey was conducted to gather statistically representative information about the perceptions of U.S. architecture firms, very important players in the material selection for a construction project. The population of interest was further narrowed down to architecture firms working with commercial building construction, which was identified as one of the most likely market segments for CLT by the experts interviewed during the first part of the study.

A distribution list was developed using the online database managed by the American Institute of Architects (AIA 2013). This association is the major professional association for licensed architects, according to personal communications with the Director of Component Communication & Resources of the AIA. The AIA's member directory provides search tools to generate lists of firms using criteria such as geographic location, type of building projects, and zip code. A distribution list was compiled with names and addresses for over 1,600 firms.

An 11-item questionnaire was developed using the results from preliminary interviews and the literature review as primary inputs. The questionnaire covered topics such as: company demographic information: location and size of company; awareness of CLT familiarity with CLT; perceptions towards CLT, and willingness to adopt the CLT building system in the future. An initial draft was sent to six professionals (including architects and academics) to assess its clarity. Next, a pre-test was conducted among 50 U.S. architecture firms, to identify clarity or inconsistency issues. Feedback from participants to the pre-test was used to improve the questionnaire.

An initial email, inviting firms in the distribution listto participate in the study was sent on December 2013. Two reminder emails were sent to those participants that did not complete the questionnaire, with one week separation between communications. The survey was closed in January 2014. Responses were downloaded and analyzed using standard statistical techniques and statistical software SPSS (IBM 2013).

RESULTS

Interviews With CLT Experts

In this section, the major results from the interviews with CLT experts are presented. Also provided are results from the research literature related to the experts' assertions.

CLT Characteristics as a Building Material

In regards to its environmental performance, several studies have concluded that CLT could be used as a more environmentally friendly alternative to concrete and steel (Chen 2012, Darby et al. 2013, John et al. 2008). Almost all interviewees agreed that the carbon sequestration and the lower greenhouse gas emissions associated with the use CLT is one of its most important environmental benefits. Specifically, one respondent mentioned that Life Cycle Analysis (LCA) of existing CLT buildings showed that these buildings have a negative carbon footprint.

CLT experts interviewed noted the favorable properties of wood in respect to heat transfer and storage, especially compared to traditional structural materials. Experts also mentioned that wood in CLT panels act as a thermal mass that stores heat during the day and releases it at night. According to one of the interviewees, the insulating capacity of CLT could also allow significant reductions in the amount of insulation needed to achieve a lower energy consumption (Reijnders et al. 1999).

According to our interviewees, CLT allows the use of underutilized and low-quality timber, since CLT is made of small components assembled and glued together, and the quality of individual pieces is not as critical as with other timber-based building components. Two manufacturer representatives stated that the biggest environmental benefit of CLT came from the potential for using underutilized forest resources to manufacture the panels.

The structural advantages of CLT mentioned by experts are in part related to the intrinsic physical and mechanical properties of wood as a construction material. The cross-laminated configuration of CLT panels act as reinforcement of the whole panel, adding to dimensional stability and allowing panels to span and carry load in both directions (Turner 2010, Van de Kuilen et al. 2010). One participant mentioned that "… [CLT is] as strong and [performs] as well as concrete but it weighs one-sixth of concrete." In regards to the strength-to-weight ratio, one interviewee also stated that the reduced weight of the structure enabled substantial savings on the foundation construction.

The majority of experts interviewed indicated that the structural characteristics of CLT make it a viable alternative to concrete structures, especially in high-rise constructions (over 6 stories). A report by the architecture and engineering firm Skidmore, Owings and Merrill proposed a 42-storey CLT-concrete hybrid building in Chicago, called Timber Tower Research Project (SOM 2013). More recently the architecture studio Rüdiger Lainer and Partners (RLP 2015) has designed the HoHo Wien, a project for a new 24 story CLT residential building in Vienna. One of the engineers interviewed for this study mentioned some skepticism about the fact that wood could be used for high-rise structures in the future, since so far the highest building modeled in the laboratory is 15 stories high. Regarding the seismic performance of CLT-base systems, interviewees with a background in engineering stated that CLT panels could perform satisfactory under lateral loading. It has been proposed by several authors that CLT-based constructions perform well under lateral forces and also possess ductility due to its multiple, small connections (Winter et al. 2010).

Three CLT experts interviewed stated that one of the main benefits of using CLT came from its design flexibility. According to one respondent, CLT allows covering long spans without intermediate supports; something that would be too complex or impossible to attain using wood in traditional ways. For example a CLT panel with 7 layers (9 inch thickness) can be used to cover spans of up to 25 feet (Malczyk 2011).

Some of the respondents also stressed the fire performance of CLT elements. Research conducted by several authors (FPInnovations 2013, Frangi et al. 2009, Karacabeyli and Douglas 2013) state that wooden structural elements of large sections such as CLT panels have desirable fire resistance properties, mainly because of wood's particular charring properties. Respondents mentioned that this behavior allows the structural element to maintain its strength and dimensional stability without collapsing in an abrupt way, potentially providing time for the evacuation of occupants from the building. Moreover, one of the interviewees, working at a national research facility, mentioned that CLT panels, due to their thickness and airtightness connection between elements, provide an extremely advantageous barrier, limiting the spreading of smoke and fire.

From the 10 expects interviewed, 9 recognized the speed of construction as one of the main cost advantages of building with CLT. More specifically, one interviewee mentioned that CLT panels "…can be installed in one-third of the time compared to other products." Respondents also stated that faster construction means fewer chances for on-site accidents, all of which reduces total costs associated with the construction process. Interestingly, 2 out of 10 respondents mentioned that the speed of construction was particularly attractive to developers, who can recover their investments more quickly: "…[CLT] can go up so quickly that the people who are paying the bills for the projects can start making money from their investment much sooner" and "…so you save time, and get to move into that building sooner and the savings from that alone are quite substantial."

Interestingly, the large volume of wood required to manufacture CLT panels, which was mentioned by some of the respondents as an advantage (enhancing the environmental, structural, fire and thermal performance of the panels), was also cited as one of the system's main drawbacks. One of the researchers interviewed, estimated that CLT panels need almost three times more wood to make than a wood-frame counterpart. Moreover, some interviewees added that the larger volume of material required could also affect the price-competitiveness of wood against traditional materials, and the public perceptions of the system, as one respondent pointed out: "…People will say that perhaps it is a lot of fiber engaged in CLT," while another respondent added that the depletion of our forests "… Is a misconception because countries such as ours [Canada], with good forest management practices, do not have deforestation concerns."

The acoustic performance of CLT structures was also mentioned by some of the interviewees as a disadvantage. One researcher stated that acoustic problems arise due to lack of proper linings or mistakes during the installation of the system. Research conducted by Gagnon (2011) found that due to its massive and airtight nature, CLT assemblies could achieve good acoustic ratings and provide adequate noise control for both airborne and impact sound transmissions.

Awareness of CLT in the architecture community

Experts interviewed were also asked about their thoughts on the level of awareness of Cross-Laminated Timber among U.S. architects. Their responses can be grouped in two categories. Half of the experts interviewed indicated that awareness is about CLT is currently low or very low. Two researchers agreed that professionals not familiar with the wood industry are less likely to have heard about CLT, with one respondent stating that "… Because the marketing for this product is coming from the wood industry, people not connected with [the sector] are not aware of the product." A second group of respondents indicated that the level of awareness of CLT in the architecture community was intermediate and steadily growing over the past five years as a consequence of the increased promotion of CLT by organizations that promote the use of wood in the U.S., such as WoodWorks (Woodworks 2015).

Interestingly, one participant of the study stated that the level of awareness is likely to be "Higher in the architectural area [as] they tend to know about it, whereas from the engineering standpoint, it is lower, [since] they are less knowledgeable about wood materials." The same participant justified the statement by explaining that the national engineering curriculum does not include in-depth information of wood as a construction material. For this reason, engineers tend to be less aware of wood-based construction alternatives, and thus more inclined to choose other materials that were extensively covered in their educational programs, such as concrete and steel.

Barriers to the adoption of CLT in the U.S.

The majority of respondents interviewed stated that, by the time this study was conducted, the main barrier for the adoption of CLT in the U.S. was its compatibility with the building code. At the time of this study, designers who wanted to use CLT for a project were required to request a special permission to local authorities. In 2013, the American Wood Council created task committees to begin the process of adding "heavy timber" (e.g., CLT) to its National Design Specifications (NDS) and ultimately to the International Building Code. The final decision on the proposed language was made in late 2014. The approved code, including CLT under the Code's Heavy Timber classification, was made available for jurisdictions to adopt in early-mid 2015 (International Code Council 2015)

Another major barrier mentioned by interviewees was the availability of information and education about CLT. The participants with a background in architecture stated, "… architects and engineers are aware [of CLT] but [between] being aware [and] being proficient, there is [a] lack of education." The same respondent later added: "It is going to take a little time to understand the product and probably [there is a] need of training, seminars, or similar activities, to get people more comfortable [with CLT]."

The limited availability of CLT in the domestic market was also seen as an important barrier to the successful adoption of the material in the U.S. market. One

Respondent Characteristic	Percent of Respondents (%)
- - U.S. Region - -	
Northeast	14.5%
South	30.2%
Midwest	17.9%
West	21.1%
Alaska	0.0%
Hawaii	0.6%
Multi-Region	15.7%
- - Firm Size - -	
1 - 4 Employment	52.4%
5 - 9 Employment	21.4%
10 - 19 Employment	10.5%
20 - 99 Employment	12.0%
100 or more Employment	3.4%

Table 1. Survey Participants' Firm Location and Size (by Number of Employees) . N=351

respondent declared, "…if you don't have any capacity or any production in the United States then […] no one knows about this product." So far, only a handful of small projects have been built with CLT, with imported panels. As of December 2015, there were only three CLT producers in the United States; all of them in the Western half, and only one APA/ANSI-certified.

Cost-competitiveness of CLT

Experts were asked about the competitiveness of CLT compared to traditional building systems. The majority of interviewees agreed that CLT could be cost-competitive as an alternative to concrete structures and for building over 6 stories high. These results are in accordance with a preliminary research conducted by FPInnovations. A manufacturing representative from Europe mentioned that the cost-competitiveness of CLT should not only be seen as initial investment, but through the whole life cycle of the building, adding that "[CLT is] cost-competitive because it already has thermal insulation, […] and for sure it might be a little bit more expensive in the beginning, but when you also include the maintenance costs it turns out to be absolutely cost-competitive."

Potential for adoption of CLT

The last question asked to interviewees was intended to gain insight on the perceived potential for adoption of CLT in the U.S. Most experts interviewed agreed that the system had great potential to become an environmentally -friendly alternative to traditional materials like concrete or steel. Two researchers and one architect agreed that adoption was likely to depend on regional differences, with regions with a stronger tradition in wood construction more likely to adopt CLT. In regions were concrete and steel have a stronger presence, the adoption process could face more challenges. As one researcher stated, the adoption of CLT "…Would face challenges in the South because of [the concern for] termites, this might require [chemically] treating CLT. But in the Northern, Eastern, and Western regions of the United States, I think there is a big potential for buildings constructed with CLT." Interestingly, one of the respondents stated that the potential for the wide adoption of CLT adoption was intrinsically related to the "green building" movement, indicating that this movement is the "wild card" to the successful adoption of wood-based construction materials such as CLT.

Survey of U.S. Architecture Firms

The online survey was sent to a total of 1,627 U.S. architecture firms, from which 351 responded. Accounting for incomplete responses, undeliverable emails and firms that declined to participate, an adjusted response rate of 22.7% was calculated. Table 1 shows de demographic information of respondents, specifically location and firm size. The responses to the survey are summarized in this section.

Material's attributes considered during the material selection process

In order to learn what architecture firms evaluate when selecting a structural system, participants were asked to rate the importance of a number of attributes of construction materials. Table 2 shows the count of responses and percentages obtained for each characteristic. In accordance to the results obtained from the interviews to CLT experts, structural performance and durability, which are also related to the structural performance of a structure, were rated the highest. The same can be said for fire performance, which was also between the characteristics rated with the highest importance. On the other hand, earthquake performance, which is certainly related to the structural performance and safety of the structure was rated as one of the least important material characteristics; which may be explained by the uneven distribution of seismic activity across the U.S. When comparing how earthquake performance is perceived in the different regions, more

Table 2. Survey Participants' Responses Regarding the Importance of Material Characteristics When Selecting a Construction Material, N=351.

Material Characteristics	Very Important	Important	Somewhat Important	Not At All Important
	- - Percent of Respondents (%) - -			
Environmental Performance	35.9%	49.3%	12.8%	1.4%
Structural Performance	82.6%	16.0%	0.9%	0.3%
Economic Performance	55.0%	40.2%	4.3%	0.3%
Aesthetics	59.5%	34.5%	4.6%	0.6%
Fire Performance	43.3%	44.7%	9.7%	0.9%
Earthquake Performance	16.8%	28.2%	33.3%	20.5%
Availability in the Market	35.6%	54.4%	9.1%	0.3%
Acoustic Performance	7.4%	43.0%	42.2%	6.3%
Durability	61.3%	36.5%	1.4%	0.3%
LEED Credits	4.8%	20.2%	51.3%	23.1%
Cost of Post-Construction Maintenance	28.5%	54.7%	15.4%	0.9%

firms located in the western regions and Hawaii consider earthquake performance as "very important" in material selection than in other regions (37.8% and 50.0% of respondents, respectively, about three to four times the percentages in all other regions). The importance of features related to the economic performance, such as availability in the market and maintenance costs are highly rated possibly because of their influence on the economic feasibility of a development, a topic that also a raise during the interviews conducted for the first part of this study. Availability in the market was seen as particularly important for architecture firms in Hawaii, presumably because of the high logistic cost of bringing materials from continental U.S. or other locations.

Level of awareness of CLT among architecture firms

One of the main objectives of this research was to determine the level of awareness about CLT in the U.S. architecture community. Participants were asked to indicate their familiarity with CLT. Table 3 shows the results from this question. Overall, only 4.3% of respondents indicated being "very familiar" with CLT, while 18.5% said they "have not heard about CLT." Results from the survey are consistent with what was stated by experts interviewed during the first part of this study. This demonstrates that there is still a significant need for education and diffusion of information.

Perceptions about CLT

The market success of a product greatly depends on how potential adopters and customers perceive the products' attributes. With this purpose, architecture firms were asked in this survey to evaluate CLT based on eleven criteria. Responses to this question are presented in Table 4.

Once more, responses obtained from the architecture firms seem to coincide with those from the experts interviewed. Respondents to the survey indicated that the most salient attributes of CLT were its structural and environmental performance, and its aesthetic characteristics; which were rated as "excellent" or "good" by 68.5%, 67.7%, and 62.2% of respondents, respectively. Moreover 38.1% of respondents perceived the economic performance of CLT as "excellent" or "good".

To further understand these responses, the relationship between the level of awareness and how attributes were rated was analyzed by performing statistical tests. A statistically significant relationship was found between awareness and perception of CLT's structural performance, meaning that the more familiar respondents were about CLT, the better they perceived its structural performance (86.6% of respondents that are "very familiar" with CLT stated that its structural performance

Table 3. Survey Participants' Responses Regarding Their Familiarity With CLT. N=351

Level of Awareness	Percent of Respondents (%)
Very Familiar	4.3%
Somewhat Familiar	37.9%
Not Very Familiar	39.0%
Have Not Heard About It	18.5%

was “excellent” or “good.”)

When asked about the perceived barriers to the future implementation of CLT in the U.S., availability of the product in the national market, availability of technical information, and compatibility with the existing Building Code, were rated as “large barrier” or “may be a barrier”, by 94.1%, 77.2%, and 62.2% of respondents, respectively. Both these responses show similar perceptions among CLT experts and U.S. architecture firms. Initial cost was also seen as a potential barrier with 90.9% of respondents indicating that cost is a “large barrier” or “may be a barrier.”

Perceived suitability of CLT for different building types

Architecture firms were asked about their perceptions on the most appropriate types of building for the use of CLT. Table 4 summarizes the results to this question. For commercial buildings, 25.2% of the participating firms indicated that CLT could be “very appropriate” for this type of buildings and 50.7% indicated that it could be “somewhat appropriate.” Results also show that CLT was thought to be “very appropriate” or “somewhat appropriate” for government (48.4%) and transportation related buildings (44.4%). Respondents to the survey were allowed to indicate other suitable applications for CLT. The most frequent “other” applications mentioned were religious buildings, such as churches or ministries, restoration of historic constructions and agricultural structures.

Willingness to adopt CLT

The third objective of this study was to determine the likelihood of the U.S. architecture community to adopt CLT if it were available in the market. This information is essential to evaluate the potential market success of CLT in the U.S. More than half respondents (50.7%) indicated uncertainty about their likelihood to use CLT in one of their building projects if it was available in the U.S.; this finding is consistent with the level of awareness reported previously, as professionals would be hesitant to adopt a material with which they are not highly familiar. Only 6.6% of respondents indicated that they were “unlikely” or “very unlikely” to adopt CLT in future projects.

Likelihood to adopt CLT for high-rise buildings

Preliminary studies conducted by FPInnovations (2011) as well as the results obtained from the interviews conducted for the first part of this study indicate that CLT would be cost-competitive for high-rise buildings as a more environmentally-friendly alternative to concrete or steel structures. Therefore, firms participating in the survey were asked about their thoughts on the likelihood of CLT being adopted for buildings over six stories in the U.S. Of all respondents, 42.0% indicated that the likelihood of CLT being used for high-rise structures was “very high” or “high,” and 28.0% of respondents said that it was “unlikely” or “very unlikely” that CLT would be used in high-rise construction. In order to further assess the relationship between level of awareness and likelihood to adopt CLT in the future, a statistical test was performed, and results showed that as participants’ familiarity with CLT increased, they were more likely to see high-rise building as a likely application for this construction system.

CONCLUSIONS

The main goal of this research was to assess the market potential to the adoption of CLT in the U.S. Specifically, this study gained insights from experts about the level of awareness and perceptions about CLT in the U.S. construction industry, and assessed the level of awareness, perceptions and willingness to adopt CLT among U.S. architecture firms.

Results from both the interviews to CLT experts and the survey to U.S. architecture firms indicate that the main benefits of CLT-based systems come from using an environmentally-friendly material (wood) compared to more traditional materials, such as concrete or steel, especially in some applications. Being a prefabricated structural system, CLT offers the advantage of faster construction time and reduced overall building costs, when compared to traditional construction systems. Experts interviewed attribute these savings to the reduced labor requirements, the fast and simpler assembly, and the reduced on-site waste and off-site disturbances. In regards to the structural capabilities of the system, the majority of experts interviewed mentioned that, due to the massive amount of wood used in CLT panels, their strength-to-weight ratio has expanded the opportunities for the use of wood in countless applications (especially for covering long spans as slab elements, or as load bearing plates and shear walls), and has reduced foundation costs. During the first part of the study, interviewees were also asked about the most common perceived drawbacks of CLT. Among the responses, acoustic and vibration performance were mentioned the most. The volume of wood required to manufacture the panels was also mentioned as a drawback. Among architecture firms, cost of post-construction maintenance and acoustic performance and were rated the lowest with only 3.8%, 4.9% of survey respondents stating that CLT panels’ performance on these aspects was “excellent.”

When asked about the level of awareness about CLT among U.S. architects, respondents from both studies agreed that the awareness is still low in the U.S., but has been steadily rising over the years. Only 4.3% of U.S. architecture firms responding to our survey declared to be “very familiar” with CLT. Some of the experts interviewed suggested the existence of regional variances in the level of awareness, proposing the idea that regions with stronger wood-based construction tradition are more likely informed about novel wood-based building materials, such as CLT.

During both studies participants were also asked about the predominant perceived barriers to the adoption of CLT in the country. The main barriers mentioned were the availability of CLT in the U.S. market (which can significantly increase the final cost of the construction, due to import and transportation charges), building code compatibility issues, and common misconceptions of wood as a building material. Interestingly, a high percentage of participants of the survey (56.6%) also saw the lack of technical information available about CLT as a potential barrier.

In accordance to a previous study conducted by FPInnovations and published in the CLT Handbook (Karacabeyli & Douglas, 2013) CLT experts’ responses about the cost-competitiveness of CLT show that the system could be cost-competitive when compared to traditional building materials. This could be particularly true for mid- to high-rise buildings (6 stories high and over), where structural requirements dictate the use of concrete or steel structural systems over wood-frame structures. There was common agreement among interviewees that CLT would not be cost-competitive for applications such as low-rise buildings and single family houses, where wood-frame construction is commonly used, due to the volume of wood required in the manufacture of the panels and its subsequent cost.

Results from the survey also showed divided opinions from architecture firms, regarding the willingness to adopt CLT. Half of the respondents (50.7%) indicated to be “uncertain” about the likelihood of them opting for CLT in the future. However, when asked about the likelihood that CLT would be used in high-rise construction, firms seemed to show more consistency in their responses. From all responses, 42.0% rated this likelihood as “very high” and “high,” and 28.0% as “unlikely” or “very unlikely.”

Results from both the interviews to CLT experts and the survey to U.S. architecture firms stress the importance that education and the timely delivery of information to target audiences can have in the acceptance and adoption of the system. The potential success of a CLT industry in the U.S. would greatly depend on information reaching the target audience, namely design and construction professionals. In this context, the current level of awareness of the U.S. architecture community signifies an opportunity for government officials and organizations promoting the use the sustainable use of wood in construction, to develop new and improve existing educational programs on the use of wood.

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Predicting Stiffness of CLT Beams Based on Constituent Lumber Properties

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ABSTRACT

This paper investigates the feasibility of using various composite assembly methods to predict the stiffness properties of CLT beams. A spreadsheet was developed to compute the predicted stiffness properties using four different mechanics based methods: (1) the Shear Analogy Method, (2) the Gamma Method, (3) the k-Method and (4) classical Transformed Section Analysis. Predicted stiffness values were compared to non-destructive bending tests of yellow-poplar (*Liriodendron tulipifera*) CLT layers and beams in both flatwise and edgewise orientations with the face grains arranged either parallel or perpendicular to the span. The Shear Analogy Method was demonstrated as one of the most versatile methods for finding the elastic and shear stiffness. The E_0/G_0 and E_0/E_{90} ratios were compared to suggested values found in literature. The results show that CLT design methods developed using softwood species are applicable to hardwood CLT.

INTRODUCTION

Previous research of CLT beams has focused on the use of softwood species groups, including spruce-pine-fir (SPF) (*Picea spp., Pinus spp., Abies spp.*) and Douglas-fir-Larch (*Pseudotsuga menziesii, Larix spp.*) (ANSI/APA 2012). However, there is an abundance of hardwood species available for CLT construction as well. The use of such wood species for CLT production expands the range of raw materials available.

This paper is part of a larger research project (NIFA/USDA Grant No. 2012- 03716 *Development of Low-Grade Hardwood Cross Laminated Timber*) focused on the investigation of low-grade hardwood use in CLT materials. Products from low-grade timber tend to be of lower value (Cumbo et al. 2003). Because many hardwood stands have received little or no forest management, there is a large quantity of low-grade hardwood material available (McGee 1982). Use of hardwood timber in CLT production would represent a high value application. If feasible, a new market could develop for hardwood lumber.

Prediction of CLT panel properties is based upon the constituent wood material properties consolidated into a composite construction. According to Chapter 3 of the *CLT Handbook* (Gagnon and Popovski 2011), three methods for predictive composite properties are given, including the Shear Analogy Method, Gamma Method, and the k-Method. Note that the U.S. Edition of the *CLT Handbook* only includes the shear analogy method (Karacabeyli and Douglas 2013). These three consolidation methods can be used to obtain the elastic stiffness (EI_{eff}) and shear stiffness (GA_{eff}) terms. The following sections give a general description of the three stiffness prediction methods, and a fourth method, the classical Transformed Section Method, which was used for comparison.

Shear Analogy Method – The Shear Analogy Method can be used to predict both the flexural stiffness (EI_{eff}) and shear stiffness (GA_{eff}) of the beams loaded in a flatwise orientation (Kreuzinger 1999). For this paper, the E_{90} is assumed to equal E_0 divided by 30 (Gagnon and Popovski 2011).

KEYWORDS: Cross-Laminated Timbers, Hardwood CLT, CLT Design, Shear Modulus, Elastic Modulus, Yellow-Poplar

The Shear Analogy Method was approved for use with softwood species having a minimum published specific gravity of 0.35 in ANSI/APA PRG 320: *Standard for Performance-Rated Cross-Laminated Timber* (ANSI/APA 2012). The use of hardwood species is not directly addressed, but Section 7.2.1 states "custom CLT grades are permitted when accepted by an approved agency in accordance with the qualification and mechanical test requirements" of Sections 8.4 and 8.5 specified in PRG 320 (ANSI/APA 2012).

Gamma Method – The Gamma Method can be used to predict the EI_{eff} values of CLT loaded in a flatwise orientation (i.e. loaded as a floor or roof panel). The Gamma Method uses the rolling shear stiffness of transverse layers to represent the stiffness of "imaginary fasteners" connecting the longitudinal layers. Thus, only the longitudinal layers are assumed to carry load. The basic assumptions of simple bending theory are applicable. It is assumed that the layers of the CLT are simply supported over a span (L). The rolling shear modulus (G_R) is assumed to be 1/10 of the shear modulus parallel-to-grain (G_0) (Mestek et al. 2008). An assumption is that G_0 is in the range of E_0 / 12 to E_0 / 20. For analytic values in this paper, G_0 was assumed to equal E_0 / 16. Shear deformations are neglected in the longitudinal layers of the CLT, but are included for transverse layers by evaluating the stiffness of the "imaginary fasteners" (i.e. rolling shear deformation) (Gagnon and Popovski 2011).

k-Method – The k-Method can be used to predict EI_{eff} *values* of CLT loaded in both flatwise and edgewise orientations (i.e. loaded as a wall or header panel). A linear stress-strain relationship and Bernoulli's hypothesis of plane cross-sections remaining plane is assumed. An assumption is that $E_{90} = E_0 / 30$. Shear deformation is not accounted for, thus this method should only be used in situations with relatively high span-to-depth (L / h) ratios greater than or equal to 30:1 (Gagnon and Popovski 2011).

Transformed Section Method - A fourth method investigated was the classical transformed section analysis, where the EI_{eff} for the composite beam is based on a transformation of the EI for the individual layers. This method has been used for analysis of other wood composites including glulam beams, I-joists, and plywood (Bodig and Jayne 1982).

The purpose of this paper was to examine the predictions of the four stiffness prediction methods described above for use with CLT panels produced from hardwoods. Individual yellow-poplar layers were tested non-destructively, then consolidated to produce a series of 5-layer CLT strip beams in both longitudinal (L-T-L-T-L) grain) and transverse (T-L-T-L-T grain) orientations. The CLT panels were tested non-destructively in both flatwise and edgewise orientations to obtain the elastic stiffness values.

A series of computer-based spreadsheets were created to calculate design parameters (EI_{eff} and GA_{eff}) of the composite CLT based on geometric and mechanical properties of individual layers using the composite consolidation methods described above. The feasibility of the design methods being used for hardwood CLT design was determined by comparing experimental values to analytical values. Further details of the project are reported by Beagley (2016).

MATERIALS & METHODS

Non-Destructive Evaluation of Yellow-Poplar Layers

Yellow-poplar lumber was defect-free and obtained from a local lumber yard. Before machining and testing, the lumber was equilibrated to a moisture content of approximately 8%. Moisture content and specific gravity samples were removed from each board. Moisture content was measured by the over-dry method according to ASTM D4442 (ASTM 2015a) and specific gravity according to ASTM D2395 (ASTM 2015b). The lumber was machined to 0.625 inches thick and 6 inches wide.

All lumber was tested non-destructively in single-point bending to measure E_0 with a simply supported span of 25 inches for longitudinal boards and 33 inches for boards to be used in the transverse sections. Every longitudinal board was tested in four equal, non-overlapping zones, each having a span of 25 inches along the length of the board. Every transverse board was tested in a single zone, having a span of 33 inches within the length of the board. Each zone was subjected to three test repetitions. All tests were performed at a displacement rate of 0.10 inch/minute. Each ply was subjected to three test repetitions. Lumber was marked to identify test sections within each board for use in computing the mechanical properties in composite CLT beams. The load-deflection curve, span, beam dimensions were used to calculate the E_0 for each board (Equation 1).

$$E = \left(\frac{P}{\Delta}\right)\left(\frac{L^3}{48I}\right) \tag{1}$$

Transverse layers were edge-glued, planed to final thickness, and cross-cut to width. The transverse plies were then tested non-destructively in bending over a span of 19.5 inches to calculate the transverse modulus of elasticity, E_{90}, (Equation 1) using the test methods described above. These non-destructive tests produced the E_0 and E_{90} stiffness values of each layer to be used as input to the four design methods.

CLT Beam Assembly

Six CLT beams each containing 5-layers orthogonally oriented to the adjacent layer were constructed. Three of the beams were designated "Longitudinal CLT" (CLT-L-1, CLT-L-2, and CLT-L-3) with three longitudinal layers and two transverse layers. The other three beams were designated "Transverse CLT" (CLT-T-1, CLT-T-2, and CLT-T-3) with three transverse layers and two longitudinal layers. Layers were attached with a crosslinked polyvinyl acrylate adhesive and clamped during curing. After manufacture, the CLT beams were machined to final dimensions of 101 inches long by 6.0 inches wide by 3.125 inches thick (Figure 1). Moisture content and specific gravity samples were removed from each CLT assembly before testing.

Non-Destructive Evaluation of Assembled CLT

The six CLT beams were tested non-destructively in single-point bending over four different simply supported spans in both flatwise (Figure 2a and 2b) and edgewise (Figure 3a and 3b) configurations. Spans tested included (A) 96.9 inches, (B) 62.5 inches, (C) 34.4 inches and (D) 25.0 inches. These spans were selected to create flatwise *L/h* ratios of 31:1, 20:1, 11:1 and 8:1. Edgewise *L/h* ratios were 16:1, 10.4:1, 5.7:1 and 4.2:1.

Figure 1: *Six assembled CLT beams*

Each sample was subjected to three test repetitions per loading of each of the four spans. All tests were performed at a displacement controlled rate of 0.10 inches per minute.

The load-deflection curve, and span were used to calculate the apparent bending stiffness (EI_{app}) for each CLT (Equation 2). Separate *E* and *I* terms are not calculated for CLT beams because the composite is not a homogeneous material.

$$EI_{app} = \left(\frac{P}{\Delta_{TOTAL}}\right)\left(\frac{L^3}{48}\right) \qquad (2)$$

Analysis of Experimental Data

Equation 2 calculated the EI_{app} value based upon the total deflection of the beam (Δ_{TOTAL}). The deflection of the CLT beams can be divided into a bending contribution ($\Delta_{BENDING}$) related to the bending stiffness, EI_{eff} and a shear contribution (Δ_{SHEAR}) related to the shear stiffness GA_{eff}.

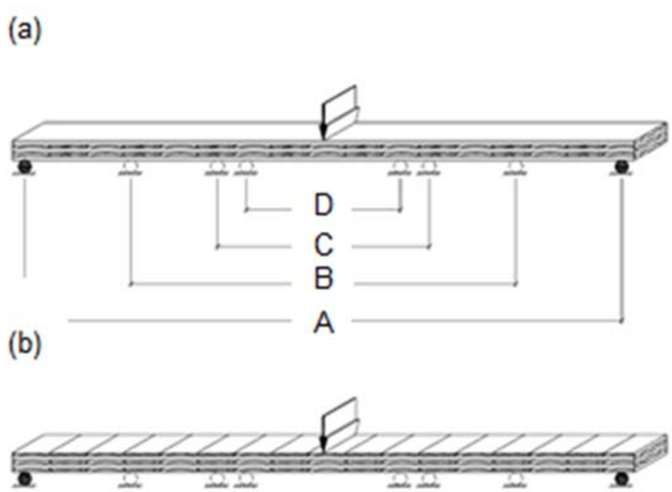

Figure 2: Flatwise orientation of (a) Longitudinal CLT and (b) Transverse CLT over all four spans.

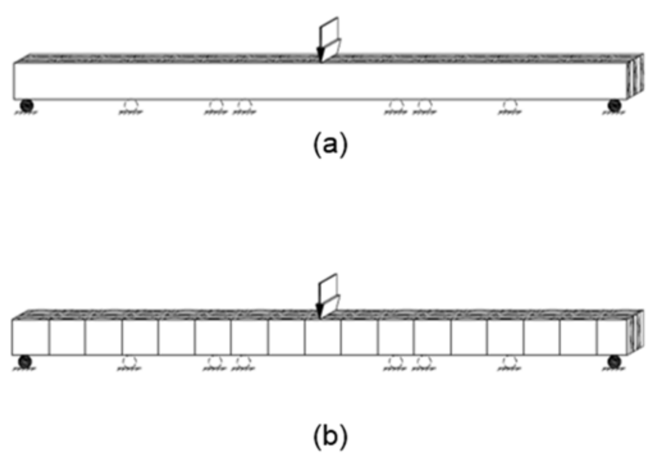

Figure 3: Edgewise orientation of (a) Longitudinal CLT and (b) Transverse CLT over all four spans.

For most wood beams shear deflection contributions are ignored or assumed less than 10% of the total deflection. However, the decreased shear stiffness of the cross-ply layers in CLTs requires calculation of the shear stiffness term for accurate assessment of the bending stiffness.

The EI_{eff} and GA_{eff} terms can be calculated using a multiple span regression method based on the shear modulus calculation of wood beams given by ASTM D198 (ASTM 2015c) and originally described by Gromala (1985). The total deflection of the beam is equal to the bending deflection and shear deflection (Equation 4). The total deflection can be solved for by using the EI_{app} term, and the bending and shear deflection equations using EI_{eff} and GA_{eff}, respectfully are shown in Equation 5.

$$\Delta_{TOTAL} = \Delta_{BENDING} + \Delta_{SHEAR} \tag{4}$$

$$\Delta_{TOTAL} = \frac{PL^3}{48EI_{app}} = \frac{PL^3}{48EI_{eff}} + \frac{PL}{4\kappa GA_{eff}} \tag{5}$$

The parameter $\kappa = 5/6$ is a shape factor for a rectangular cross-section (ASTM 2015c). Dividing out like terms and solving for $1/EI_{app}$ yields Equation 6.

$$\frac{1}{EI_{app}} = \frac{1}{\kappa GA_{eff}}\left(\frac{12}{L^2}\right) + \frac{1}{EI_{eff}} \tag{6}$$

Equation 6 has the form of $y = mx+b$, where y is the inverse of EI_{app}, m is the inverse of κGA_{eff} , x is $(12/L^2)$, and b is the inverse of EI_{eff}. The y and x variables were calculated for spans A, B, C and D. Then m (slope of line) and b (intercept of line) were found using regression to find the EI_{eff} and GA_{eff} values.

RESULTS AND DISCUSSION

Experimental vs. Analytical Values

Experimental EI_{eff} and GA_{eff} values were calculated for both flatwise and edgewise orientations using the multiple span regression method. Then, analytical EI_{eff} and GA_{eff} values were calculated using the individual layer properties of each CLT beam from the four prediction methods. The experimental EI_{eff} was compared to the analytical EI_{eff} values for both flatwise (Table 1) and edgewise (Table 2) orientations. The experimental GA_{eff} was compared to the analytical GA_{eff} for flatwise orientation in Table 3.

Under-predicted (negative) values indicate that the predicted value was less than the experimental value, and vice versa for over-predicted values. Percentage errors of ≤±10% were considered to be accurate prediction of values.

The following observations were made from Table 1 about beams tested in a flatwise orientation:

- The average experimental EI_{eff} values for Longitudinal CLT were approximately 3.43 times greater than the Transverse CLT across all methods.
- Shear Analogy Method accurately predicted the EI_{eff} for Longitudinal CLT (average error of -4.9%) and Transverse CLT (average error of -2.5%). This method was the most accurate prediction for the Transverse CLT.
- The Gamma Method consistently under-predicted the EI_{eff} for Longitudinal CLT (average error -28.1%) and greatly over-predicted the EI_{eff} for Transverse CLT (average error of 145%).

Table 1. Flatwise Bending Results Comparison of Experimental EI_{eff} to Analytical EI_{eff}

Beam ID	Experimental[1] EI_{eff} ($\times 10^6$ lb-in^2)	Shear Analogy Method		Gamma Method		K-Method		Transformed Section Analysis	
		EI_{eff} ($\times 10^6$ lb-in^2)	% Diff.[2]	EI_{eff} ($\times 10^6$ lb-in^2)	% Diff.[2]	EI_{eff} ($\times 10^6$ lb-in^2)	% Diff.[2]	EI_{eff} ($\times 10^6$ lb-in^2)	% Diff.[2]
CLT-L-1	23.1	25.4	10.0%	19.4	-16.0%	24.9	7.8%	26.0	12.6%
CLT-L-2	28.2	22.4	-20.5%	16.2	-42.6%	23.4	-17.0%	24.0	-14.9%
CLT-L-3	26.4	25.3	-4.2%	19.6	-25.8%	25.4	-3.8%	26.0	-1.5%
CLT-T-1	6.58	5.96	-9.4%	18.3	178%	4.48	-31.9%	8.50	29.2%
CLT-T-2	7.78	7.66	-1.5%	18.4	137%	5.66	-27.2%	7.97	2.4%
CLT-T-3	8.26	8.55	3.5%	18.2	120%	6.33	-23.3%	13.2	59.8%

[1] Multiple Span Regression Method (Equation 6)

[2] % Difference = (Analytical - Experimental)/Experimental * 100%

- The k-Method accurately predicted the EI_{eff} for Longitudinal CLT (less than -4.3% average error) and consistently under-predicted the EI_{eff} for Transverse CLT (less than -27.5% average error).
- Transformed section analysis most accurately predicted the EI_{eff} for Longitudinal CLT (1.2% average error) and consistently over-predicted the EI_{eff} for Transverse CLT (30.5% average error).

The comparison of edgewise EI_{eff} of experimental and analytical predictions is shown in Table 2. Only the k-Method and Transformed Section Analysis were used, since the Shear Analogy and Gamma methods were not applicable for predicting beams loaded in edgewise orientation. The following observations were made from Table 2 for beams tested in an edgewise orientation:

- The experimental EI_{eff} values for Longitudinal CLT were approximately 1.4 times greater than for Transverse CLT across all methods.
- The k-Method most accurately predicted the EI_{eff} for Longitudinal CLT (average error of 3.2%) and consistently under-predicted the EI_{eff} for Transverse CLT (-30.3% average error).
- Transformed section analysis accurately predicted the EI_{eff} for Longitudinal CLT (5.1% average error) and accurately predicted the EI_{eff} for Transverse CLT (less than 3.7% average error).
- Although k-Method was not the most accurate for predicting EI_{eff} for Transverse CLT of methods proposed in the CLT Handbook [3], the k-Method has the advantage of predicting EI_{eff} for beams tested either flatwise or edgewise.

The comparison of experimental to analytical shear stiffness GA_{eff} for the flatwise CLT beams is shown in Table 3. An E_0/G_0 ratio of 16:1 was assumed for the Shear Analogy Method to calculate the analytical values. The Gamma, k-Method and Transformed Section Analysis methods were not applicable for predicting GA_{eff} for beams and the Shear Analogy Method prediction only applies to flatwise beams. CLT-T-1 had a much lower GA_{eff} value than CLT-T-2 and CLT-T-3, indicating that this may be an outlier data point. Therefore, CLT-T-1 was not included within the average error values described below:

- The experimental GA_{eff} values for Longitudinal CLT were approximately 8 times less than for Transverse CLT.
- The Shear Analogy Method consistently under-predicted the GA_{eff} for Longitudinal CLT (less than -70% average error) and accurately predicted the GA_{eff} for Transverse CLT (less than 1% average error).

The sensitivity of the Shear Analogy Method to the assumed E_0/G_0 ratio is shown in Figure 4. The horizontal lines of Figure 4 are the experimental averages of GA_{eff} for the flatwise Longitudinal and Transverse CLT, while the curve represents the predicted GA_{eff} for E_0/G_0 ratio ranging from 1:1 to 30:1, computed using the Shear Analogy Method. An E_0/G_0 ratio of approximately 5:1 intersected the experimental GA_{eff} values and may be a more suitable value for predicting the shear stiffness of the yellow-poplar CLT beams tested in this project.

Table 2. Edgewise Bending Results Comparison of Experimental EI_{eff} to Analytical EI_{eff} for Edgewise Bending of CLTs

Beam ID	Experimental[1] EI_{eff} ($\times 10^6$ lb-in^2)	K-Method		Transformed Section Analysis	
		EI_{eff} ($\times 10^6$ lb-in^2)	% Diff.[2]	EI_{eff} ($\times 10^6$ lb-in^2)	% Diff.[2]
CLT-L-1	60.5	69.2	14.3%	69.2	14.3%
CLT-L-2	67.8	64.6	-4.7%	64.6	-4.7%
CLT-L-3	70.5	70.4	-0.1%	74.5	5.7%
CLT-T-1	41.8	26.1	-37.6%	37.5	-10.3%
CLT-T-2	49.1	34.2	-30.3%	50.0	1.8%
CLT-T-3	49.4	38.1	-22.9%	59.4	20.2%

[1] Multiple Span Regression Method (Equation 6)

[2] % Difference = (Analytical - Experimental)/Experimental * 100%

Table 3. Comparison of Shear Stiffness (GA_{eff}) Experimental and Analytical Values for Flatwise Bending of CLTs

Beam ID	Experimental[1] GA_{eff} ($\times 10^6$ lb-in^2)	Shear Analogy Method	
		GA_{eff} ($\times 10^6$ lb-in^2)	% Diff.[2]
CLT-L-1	1.43	0.353	-75.3%
CLT-L-2	0.93	0.353	-62.0%
CLT-L-3	1.24	0.346	-72.0%
CLT-T-1	1.89	0.425	-77.5%
CLT-T-2	7.78	7.66	1.5%
CLT-T-3	8.26	8.55	3.5%

[1] Multiple Span Regression Method (Equation 6)

[2] % Difference = (Analytical - Experimental)/ Experimental * 100%

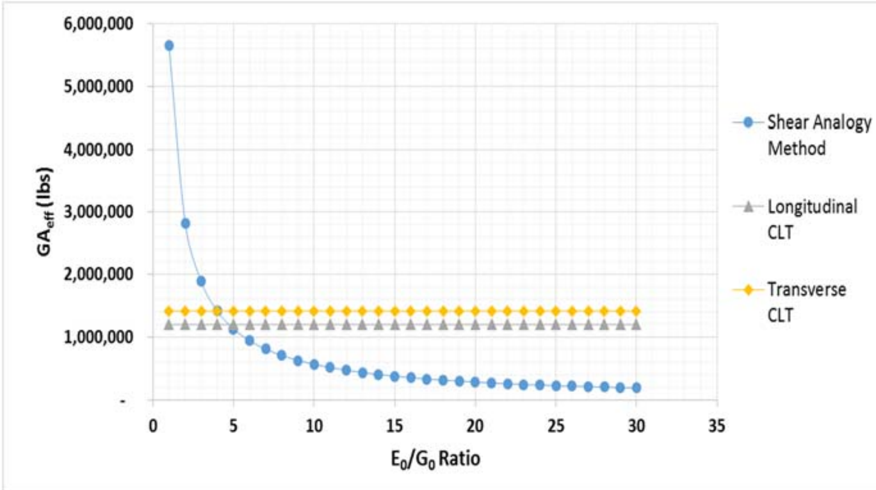

Figure 4. Effect of E_0 / G_0 ratio on GA_{eff}.

The E_0 to E_{90} ratio was measured from the experimental results and compared to the assumed value of E_0/E_{90} = 30:1 [3]. The measured range of E_0/E_{90} for the CLT beams was 16:1 to 26:1, as shown in Figure 5, with the average value being 22:1. The difference in assuming E_0/E_{90} = 16:1 versus E_0/E_{90} = 30:1 results in a 0.73% difference and 0.78% difference in the computed EI_{eff} for the Shear Analogy Method and k-Method, respectively. The assumed E_0/E_{90} = 30:1 under-predicted the experimentally measured value of EI_{eff}. However, the ratio value change does not greatly affect the EI_{eff} value. Thus, assuming E_0/E_{90} = 30:1 is appropriate for this project.

SUMMARY

Yellow-poplar lumber was used to create six 5-layer hardwood CLT beams. The lumber was tested non-destructively to measure the load and deflection for use in calculating E_0 and E_{90}. Individual boards were then assembled into 5-layer CLT beams. The CLT beams were non-destructively tested in bending over four simply supported spans to measure the load and deflection for use in calculating EI_{eff} and GA_{eff}. A spreadsheet was developed to compute the analytical EI_{eff} and GA_{eff} using four different mechanics based methods: (1) the Shear Analogy Method, (2) the Gamma Method, (3) the k-Method (Gagnon and Popovski 2011) and (4) classical transformed section analysis (Bodig and Jayne 1982). The Shear Analogy Method and Gamma Method are not applicable for design of CLT loaded in an edgewise orientation. The Shear Analogy Method is the only method investigated that is applicable for predicting GA_{eff}.

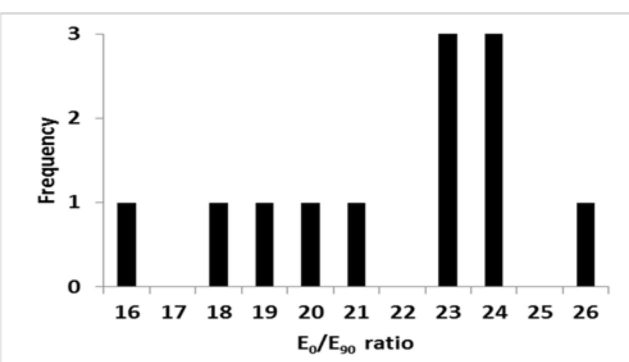

Figure 5: Frequency histogram of experimental E_0 / E_{90} ratios. (Mean E_0 / E_{90} =22.0)

The experimentally derived properties were compared to the analytically derived properties. Transformed section analysis, the Shear Analogy Method and the k-Method were all suitable for use in calculating EI_{eff} for flatwise Longitudinal CLT (floor or roof). The Shear Analogy Method was suitable for use in calculating EI_{eff} for flatwise Transverse CLT (floor or roof). Both the k-Method and transformed section analysis were suitable for use in calculating the EI_{eff} for edgewise Longitudinal CLT (header).

Neither the k-Method nor transformed section analysis were suitable for calculating the EI_{eff} for edgewise Transverse CLT (wall). Further research should be conducted to develop a more accurate design method for this loading.

An E_0/G_0 ratio of 5:1, as opposed to a value within the range of 12:1 to 20:1, was recommended for use in calculating GA_{eff} of hardwood Yellow-poplar CLT using the Shear Analogy Method. The GA_{eff} potentially could be a controlling design parameter for Transverse CLT.

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Rolling Shear Strengths of Southern Pine Cross Laminated Timber

Mengzhe Gu, Weichiang Pang PhD

ABSTRACT

Cross-laminated timber (CLT) is a relatively new engineered wood product. While CLT has gained acceptance and utilization in Europe, Australia and other countries, its applications in the United States are limited. Limited information is available on CLT made from US wood species. This paper presents the rolling shear test results of CLT panels made using one of the US wood species, Southern Pine (SP). Four types of adhesive, namely Melamine Formaldehyde (MF), Phenol Resorcinol Formaldehyde (PRF), Polyurethane (PUR) and Emulsion Polymer Isocyanate (EPI), were used to make 3-layer SP CLT panels. The characteristic rolling shear strengths of the test panels (5th percentile with 75% confidence tolerance limit) were determined for both the major and minor axes and compared to the required characteristic values in PRG-320 for V3 layup. The results showed that SP CLT panels made with PUR passed the PRG-320 rolling shear requirements in both major and minor axes.

INTRODUCTION

Cross laminated timber (CLT) is an engineered structural composite panel that is manufactured by gluing cross-wise oriented layers of lumber boards together using either vacuum or hydraulic press. CLT was first developed in Switzerland in the 1970s with further research work in Austria in the mid-1990s, which led to commercialization of structural-use CLT panels. A conventional CLT panel is typically composed of odd numbers of layers (three, five, seven or nine layers) with the grain orientation of adjacent layers perpendicular to each other. The finished panels are typically 2 to 10ft wide and with length of up to 60ft and thickness of up to 20 inches. The cross-lamination of lumber boards in CLT provides the overall dimensional stability, strength and rigidity of the panel making it ideal for replacing pre-cast concrete panels for constructing low and mid-rise commercial and multi-family residential buildings. A recent study has shown that it is feasible to construct tall wood buildings of up to 42 stories primarily using mass timber such as CLT (SOM 2013).

Keywords: Cross-laminated timber; CLT, Southern Pine; Rolling Shear; Johnson Distribution; Wood Composite; Interlaminar Shear Stress

While CLT has gained popularity in Europe, Australia and elsewhere (Brandner 2013), it has yet to become established in the US. During the preparation of this manuscript, there are only a limited number of CLT buildings constructed in the US and the CLT panels used in these buildings were imported from Europe and Canada. While there are US manufacturers that produce non-structural CLT panels (e.g. for crane mats), currently, there is only one manufacturer in the US that is certified to produce structural grade CLT panels for construction. The structural performance and behaviors of CLT made from European and other non-US wood species have been extensively studied by others (Blass et al. 2000). However, only scant body of knowledge is available for CLT made from US wood species. This paper presents the results of rolling shear tests for CLT made using one of the US wood species, Southern Pine (SP).

BACKGROUND

Wood is an orthotropic material with different mechanical properties in the three mutually orthogonal axes: Longitudinal (L), Tangential (T), and Radial (R), as illustrates in Figure 1. Rolling shear is defined as the shear stresses due to shear strain in the RT plane, and can be interpreted as the wood fibers parallel to the

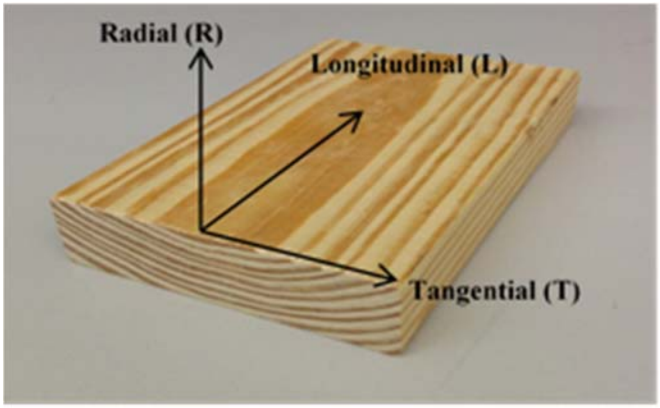


Figure 1. The principal axes of wood with respect to grain direction and growth rings.

longitudinal direction rolling or sliding “over” each other, thus, wood producing a very low rolling shear strength value.

Currently, there are multiple test methods available to determine the rolling shear properties, and it has been found that the rolling shear properties are depended mainly on wood species, growth ring orientation, lay-up, and span-to-depth ratio. A standard for performance-rated CLT called PRG-320 was recently published (APA 2012). This standard serves as an impetus towards acceptance of CLT made of US wood species, as recently the International Code Council approved the inclusion of PRG-320 qualified CLT panels as building materials in the 2015 International Building Code (IBC 2015). Kramer et al. (2014) evaluated the rolling shear behavior of three-ply Hybrid Poplar CLT with Phenol-Resorcinol-Formaldehyde (PRF) adhesive in accordance to the PRG-320 standard. The adhesive was mixed using a ratio of 2.5:1 (resin-hardener, by weight) and a spread rate of 60 lbs/1000 ft2. The Hybrid poplar CLT was pressed at a pressure of 102 psi through tightening of a series of C channels. They observed that shear through the section was the primary failure mechanism in the short-span shear tests and reported the 5% value of rolling shear strength of 76.9psi. Fellmoser and Blass (2004) evaluated the rolling shear modulus and the effect of span-to-depth ratio for Spruce CLT through a dynamic vibration test, they found that shear deformation depends significantly on the thickness of the layers vulnerable to rolling shear failure (i.e. layers with lumber oriented perpendicular to the span direction). The influence of shear on the overall bending behavior was found to be significant for span-to-depth ratios smaller than 30 for bending parallel to the grain direction and 20 for perpendicular to the grain direction. Mestek et al. (2008) conducted a comparative analysis using shear analogy method and finite element (FE) shell model. They concluded that the increase of longitudinal stress due to the effect of rolling shear deformation is a functions of the span-to-depth ratio. Zhou et al. (2014) evaluated the rolling shear properties of three-ply Black Spruce CLT by two-plate shear test and three-point bending test described in ASTM D2718 (2011) and ASTM D198 (2014), respectively. Black Spruce CLT was edge glued with fast-curing epoxy and one-component PRF, and then pressed under a pressure of 87 psi for 24 hours. They found that two-plate shear test is a more appropriate test method for assessing the rolling shear modulus and the bending test is an appropriate test method for determining the shear strength. The rolling shear strength was reported as 310 psi, obtained via a three-point bending test using a span-to-depth ratio of six. Zhou et al. (2014) concluded that shear analogy method can be used to accurately predict the deflection of CLT specimens under bending when span-to-depth ratio is relatively small. More recently, Li et al. (2014) studied the rolling shear properties using torsional shear tests and bending tests for Spruce-Pine-Fir (SPF) three-ply and five-ply CLTs. Their panels were glued with polyurethane (PUR) adhesive and pressed at two different pressures (15 psi and 58 psi). They discovered that higher pressure produced higher average rolling shear strength: 293 psi and 319 psi for the abovementioned pressures, respectively. They also found that specimens with thinner cross layers also had higher average rolling shear strength than the specimens with thicker cross layers. In summary, there is limited information regarding the rolling shear performance of Southern Pine (SP) CLT.

OBJECTIVES

Southern Pine (SP) group species (Loblolly, Longleaf, Shortleaf and Slash pines) are the most commonly available wood species in Southeast region of the US. The objectives of this study were: (1) to manufacture CLT using SP lumber, and (2) to evaluate the rolling shear properties of non-edge-glued CLT panels under out-of-plane bending and compared the rolling shear strength to the requirements in PRG-320 (APA 2012).

Test Panels Preparation

Two batches of CLT panels were manufactured using visually graded SP lumbers, namely small pilot-scale panels in a laboratory setting and full-size panels in a plant environment. The first batch of small pilot-scale 4’x4’ CLT panels were manufactured at Clemson University. The second batch of full-scale CLT panels (10’x40’) were produced by Structurlam in Penticton, Canada and shipped to Clemson University for testing. The CLT panels for rolling shear evaluation were all three

Table 1. Mix ratio and spread rate for MF, PRF and EPI.

Adhesive	Mix Ratio (Resin:Hardener	Spread Rate (lb/100 ft^2)	Platen Pressure (psi)	CAT[1] (min)	Required Press Time (hr)
Melamine Formaldehyde (MF)	100:60	63	150	30	3
Phenol Resorcinol Formaldehyde (PRF)	100:40	60	150	30	3
Emulsion Polymer Isocyanate (EPI)	100:15	72	150	10	3
Polyurethane (PUR)	N/A	60	150	40	4

[1] Close Assembly Time (CAT) refers to the time interval from substrate assembly to the application of full pressure.

layers and were manufactured using visually graded SP lumbers in accordance to the “V3” layup in PRG-320 (APA 2012): No. 2 SP lumber in outer layers parallel to the panel length and No. 3 SP lumber in center layer perpendicular to the panel length. Both the Clemson and Structurlam CLT panels were made from 2x6 SP lumbers.

Adhesives

Four different adhesives were used to make the rolling shear test panels: Melamine Formaldehyde (MF), Phenol Resorcinol Formaldehyde (PRF), Emulsion Polymer Isocyanine (EPI), and Polyurethane (PUR) adhesive. MF is typically used for manufacturing glulam and has good water resistance. Compared to other formaldehyde-based adhesives, MF also has a much lighter color (i.e. it does not stain the wood). However, the limitations of MF are the relatively high cost of melamine compared to phenolic resin and the so called “off-gassing” behavior of formaldehyde. PRF has the advantages of curable at room temperature, durable, and economical (i.e. phenol-resorcinol compounds are generally more economical than melamine). PRF is also an off-gassing adhesive, as it contains formaldehyde. However, the off-gas rate of PRF over the life of the product (i.e., beyond the production phase) is much lower than other formaldehyde resins such as MF (Brown 2005). In addition, the cured PRF may show unpleasing dark stains in the glue lines. EPI is a two-part adhesive that requires mixing prior to glue application. Due to the emulsifability of isocyanate, adequate mixing is important. Despite EPI is not an off-gassing adhesive, the main disadvantages are high cost of EPI compared to formaldehyde-based adhesives and low workability during mixing of the adhesive. PUR is a moisture-activated adhesive that is commonly used in CLT panels produced in European and Canada because it does not contain formaldehyde. However, the fire resistance of PUR is generally poorer than other adhesives such as MF. Since each of these four adhesives has its advantages and disadvantages, all four adhesives were utilized in this study to make SP CLT panels.

Table 2. Number of Specimens Produced and Tested for Major and Minor Axes Rolling Shear Strength

Adhesive	Major Axis Samples	Minor Axis Samples
MF	8	8
PRF	8	8
EPI	8	N/A
PUR	10	10

The 4’x4’ panels were made using MF, PRF and EPI while the full-size 10’x40’ panels were made using PUR adhesive. Two 4’ x 4’ panels were made each using MF and PRF. Each of the 4’ x 4’ panels were cut into eight short-span rolling shear test specimens for major and minor axis rolling shear tests. Only one 4’ x 4’ panel was made using EPI for major axis rolling shear strength evaluation. EPI was not evaluated for minor axis shear strength. This is because the major axis shear tests were first conducted and EPI was found to have the lowest major axis shear strength (See Results and Discussion). Two 10’ x 40’ PUR panels were manufactured by Structurlam. Ten major axis and minor axis rolling shear test specimens each were produced from one of the two 10’ x 40’ panels. Except for PUR, all other adhesives are two-component adhesives, which require the mixing of resin and hardener. PUR is a one-component adhesive. The resin-to-hardener mix ratio, spread rate and minimum pressing time for each of the three adhesives used in the production of the pilot-scale panels can be found in Table 1.

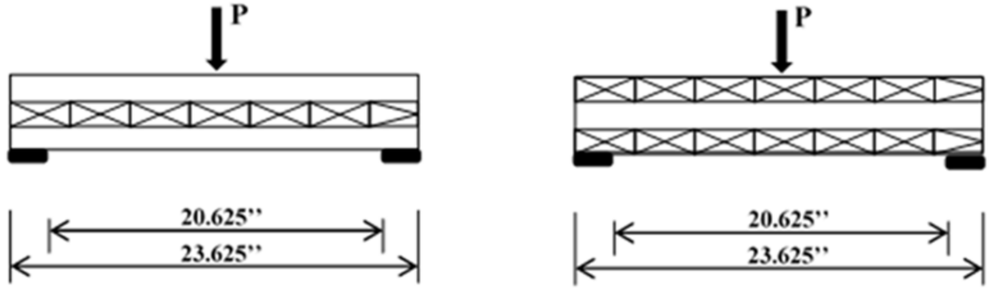


Figure 2. Three-point short-span bending test setup for rolling shear (left: major axis ; right: minor axis).

Pressing

All panels were pressed with a platen pressure of 150 psi (FPInnovations 2013) for approximately 6 hours, which exceeded the minimum 3 hours pressing time by the manufactures. After pressing, the panels were stored in an in-door environment for another 24 hours to allow the adhesives to sufficiently cured. Finally, each of the 4'x4' panels was cut into 8 pieces of short-span shear test specimens (12'' wide, 23 5/8'' long and 4 1/8'' thick specimens). 60 specimens were produced for rolling shear tests, in which 40 specimens were made at Clemson using MF, PRF and EPI and 20 specimens were made using PUR in an industrial setting by Structurlam (Table 2). EPI was not tested for minor axis. This is because major axis shear tests were first conducted and it was found that EPI had the lowest major axis shear strength; therefore, was eliminated from further minor axis shear strength evaluation.

Test Method

The rolling shear capacity of SP CLT panels were evaluated using the three-point short-span bending test approach described in ASTM D 4761 (2013). Schematic views of the three-point bending test setups for major and minor axes rolling shear tests are shown in Figure 2. All specimens were 12" wide and 4 1/8'' deep with a clear span of 20 5/8'' and a span-to-depth ratio of 5, as recommended in ASTM 3737 (2012), to ensure shear failure mode. The bearing length was 1.5'' at each of the supports. All specimens were loaded using a 150-kip capacity actuator with a loading rate of 0.05 in/min to ensure a minimum test-to-failure time of 4 minutes. The deflection was measured using a 12-in stroke draw-wire displacement sensor attached to the bottom face of the specimen at mid-span. In each test, the complete load-displacement curve, peak load and failure mode were recorded. Figure 3 shows the typical test setup for one of the major axis specimens.

Prior to each test, moisture content (MC) and density were measured for each specimen. The average MCs were all greater than 8% (Table 3), which satisfied the PRG-320 minimum MC requirement for the evaluation of mechanical properties (APA 2012).

RESULTS AND DISCUSSION

The rolling shear strength ($\tau_{rolling}$) for each test was computed using Equations 1 and 2.

$$\tau_{rolling} = \frac{P_{max}/2}{(Ib/Q)_{eff}} \qquad (1)$$

Table 3. Density and Moisture Content of Major and Minor Axis Specimens

Adhesive Type	Major Axis			Minor Axis		
	Number of Specimens	Density, lbs/ft^3 (COV)	Moisture Content, % (COV)	Number of Specimens	Density, lbs/ft^3 (COV)	Moisture Content, % (COV)
MF	8	34.5 (2.1%)	9.53% (7.3%)	8	34.7 (3.3%)	9.74 (3.6%)
PRF	8	35.9 (2.2%)	9.52% (4.9%)	8	33.7 (2.1%)	9.59 (5.3%)
EPI	8	34.7 (1.9%)	10.5% (3.7%)	--	--	--
PUR	10	30.7 (2.6%)	8.66% (4.7%)	10	30.2 (2.5%)	8.79 (7.2%)

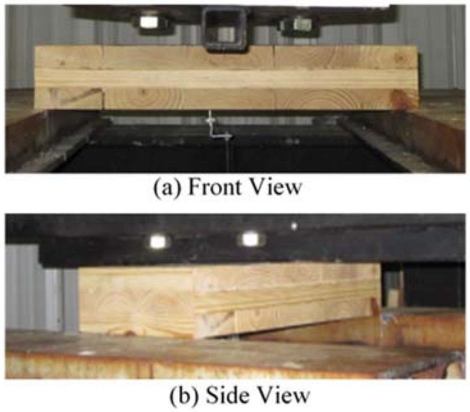


Figure 3. Typical Experimental Setup for Major Axis Rolling Shear Test.

$$(Ib/Q)_{eff} = \frac{(EI)_{eff}}{\sum_{i=1}^{n/2} E_i h_i z_i} \qquad (2)$$

where P_{max} is the peak force observed during the initiation of rolling shear failure; EI_{eff} is the effective bending stiffness; E_i is the modulus of elasticity (MOE) of layer i; h_i is the thickness of layer i, except the middle layer, which is taken as half of the middle layer thickness (Figure 4); z_i is the distance from the centroid of the layer to the neutral axis, except for the middle layer, where it is measured from neural axis to the centroid of the top half of the middle layer.

The MOE parallel to the major strength direction (E_0) for calculating effective bending stiffness EI_{eff} was obtained from the National Design Specifications for Wood Construction (NDS) (APA 2012). The perpendicular to major strength direction MOE values (E_{90}) was taken as 1/30 of E_0 (APA 2012).

Table 4. Summary of Rolling Shear Strengths for Major and Minor Axes

Adhesive	No. of Tests	Mean Rolling Shear Strength, psi (COV)
Major Axis		
MF	8	289 (9.9%)
PRF	8	353 (5.4%)
EPI	8	246 (12.2%)
PUR	10	259 (7.8%)
Minor Axis		
MF	8	243 (18.3%)
PRF	8	279 (22.0%)
PUR	10	286 (16.4%)

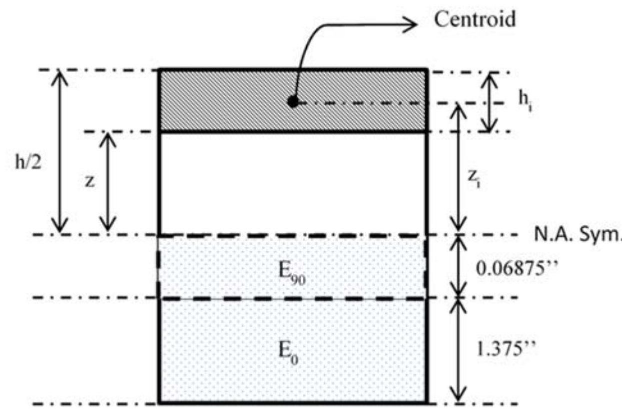


Figure 4. Schematic View of 3-Layer 'V3' Cross-Section for Calculating Rolling Shear

RESULTS AND DISCUSSION

Table 4 summarizes the major and minor axes rolling shear strengths computed using Equations 1 and 2. It should be noted that the initiating failure of five out of eight of the major axis EPI specimens was glue bond failure. These five specimens were excluded from the rolling shear strength calculations. The major axis rolling shear strengths exhibited less variability than that of the minor axis specimens. This is because the major axis test specimens failed mainly in "pure" rolling shear mode while the minor axis specimens showed combined rolling shear and bending failures. More details on the failure mechanisms of the major and minor axis tests are discussed in the next section

Failure Mechanism of Major Axis Specimens

Figure 5 shows the load-displacement curves of the major axis rolling shear tests categorized by adhesive type. Except for five of the EPI specimens that exhibited glue bond failures, the first major drop in load in each of the curve shown in Figure 5 marks the initiation of rolling shear failure. The typical rolling shear mechanism observed during major axis tests followed a sequence of three failure stages:

(1) initiation of diagonal rolling shear cracks in the middle layer near the supports (Figure 6),

(2) extension of diagonal cracks to the top and bottom layers and followed by delamination failure at one or two of the horizontal glue lines (Figure 7), and

(3) bending failure occurred due to compression (top) and/or tension failures of the longitudinal fibers in the outer layers (Figure 8).

From Figure 5, it can be seen that the CLT panel retained portion of the load carrying capacity beyond the first major failure event or drop in load. This phenomenal was

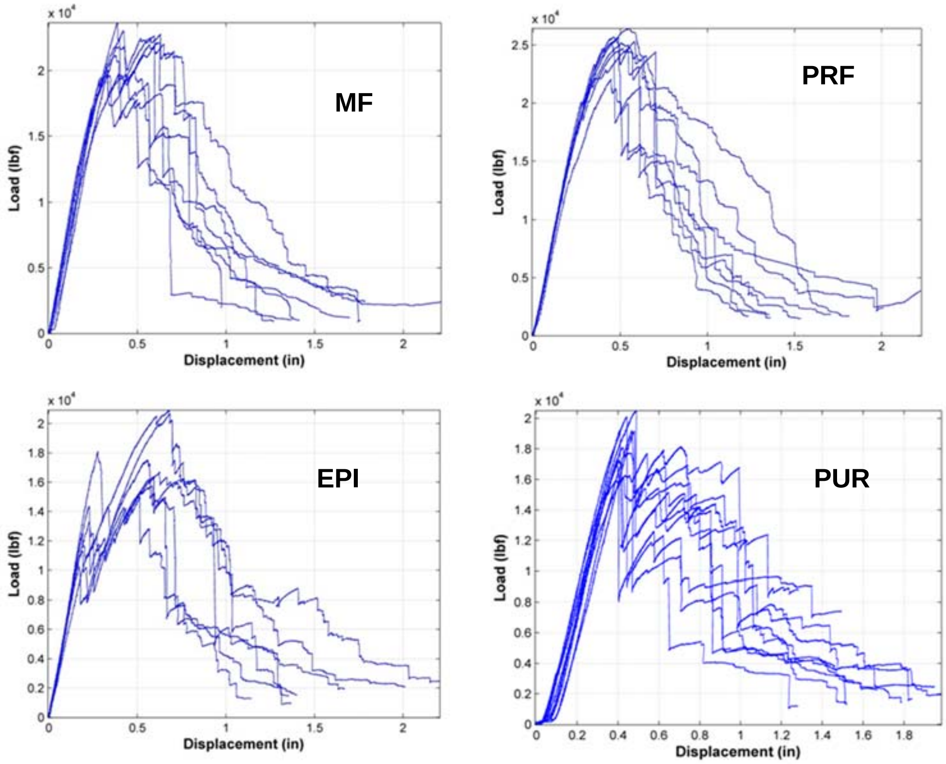


Figure 5. Load-Displacement Curves of Major Axis Rolling Shear Tests

Figure 6. Typical Rolling Shear Cracks

Figure 7. Extension of Diagonal Shear Crack into Glue Lines

Figure 8. Glue Bond Delamination (Observed in EPI Specimens) and Bending Failure

Table 5. Estimated Glue Bond Strengths for Major Axis

Adhesive Type	Mean Glue Bond Strength, (psi)	Standard Deviation, (psi)
MF	> 288[1]	26.6
PRF	> 351[1]	17.6
PUR	> 259[1]	20.2
EPI	175[2]	19.1

[1] Glue bond strengths for MF, PRF and PUR are estimated as the shear stress at the glue line when rolling shear failure occurred.

[2] Glue bond strength for EPI is calculated as the shear stress at the glue line when delamination failure occurred.

attributed to redistribution of shear force occurred after the initiation of the first major diagonal rolling shear crack. This transverse shear redistribution behavior was also observed in the shear tests by Zhou et al. (2014).

The limiting failure mode for all MF, PRF and PUR specimens was rolling shear. Pre-mature delamination along the glue lines were observed for five of the eight EPI specimens with no sign of rolling shear failure (Figure 8). These delamination failures are reflected in the first peaks of the EPI load-displacement curves shown in Figure 5. As stated, these five specimens with glue bond failures were excluded from the rolling shear statistics shown in Table 4

The glue bond strength for each test specimen was estimated by using the peak force for each of the curve shown in Figure 5 to compute the shear stress in the glue layers. Since glue bond failure was not the initiating failure mode for MF, PRF and EPI specimens, one can expect the glue bond strengths for these adhesives to be greater than the glue layer shear stresses computed using the peak loads (Table 5). For those EPI specimens with glue bond failures, the peak loads can be used to estimate the glue bond strengths. Table 6 shows the MF, PRF and PUR glue bonds were at least 64%, 100% and 48% stronger than that of the EPI specimens, respectively.

Failure Mechanism of Minor Axis Specimens

The load-displacement curves of minor axis rolling shear tests are shown in Figure 9. The failure mechanism of minor axis rolling shear specimens was different compared to the major axis. When load applied to a minor axis test specimen was gradually increased, the minor axis shear test panel exhibited the following typical failure sequence (Figure 10):

(1) opening of vertical gap closest to the mid-span in the tension side (bottom layer) of the panel. Note that the panels were not edge glued,

(2) rolling shear failure and crack initiation in the top layer in compression, and

(3) bending failure in the middle layer longitudinal boards. This ultimate bending failure typically accompanied with a very loud noise associated with rupture of wood fiber in tension.

Characteristic Rolling Shear Strength

In order to qualified for structural CLT application, the 5th percentile rolling shear strength from tests with 75% confidence tolerance limit for SP CLT must meet the published values, known as characteristic test values, in Table 1 of PRG-320 (APA 2012). To evaluate the characteristic test values, the major and minor rolling shear strengths for each of the adhesive type were fitted to Normal, Lognormal, Gumbel, Frechet, Weibull and Unbounded Johnson distributions. For fitting the major

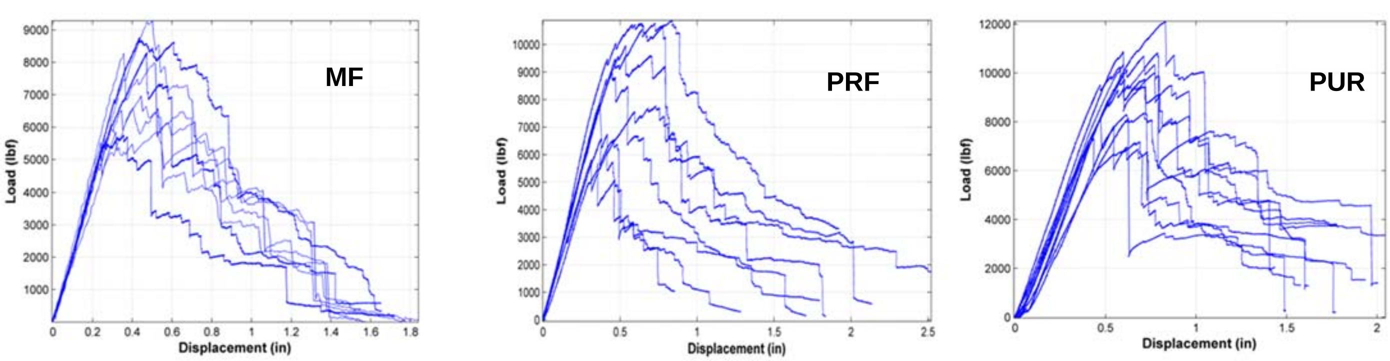


Figure 9. Load-Displacement Curves of Minor Axis Rolling Shear Tests

Figure 10. Failure of a Minor Axis Specimen

axis rolling shear strength, it was determined that the Unbound Johnson Distribution (SU) is the most suitable distribution for capturing the extreme values at low percentile region. The fitted Johnson SU distributions for major axis specimens are shown in Figure 11 (left). Note that for the EPI major axis specimens, only the three tests with rolling shear failures are fitted to Johnson SU distribution (five other tests failed due to delamination of glue lines). For minor axis specimens, normal distribution was determined to be the best-fit distribution (Figure 11, right).

The required characteristic test values listed in Table 1 of PRG-320 (APA 2012) is the minimum required one-sided tolerance limit (TL) associated with 5th percentile and 75% confidence level. To be more specific, it is a one-sided lower TL as defined by ASTM D2915 (2011). Equation 3 was used to determine the characteristic test values (Y_L). For the minor axis test data fitted to normal distribution, a tolerance factor k is determined such that the TL intervals cover at least a proportion p of the population with confidence γ

$$Y_L = \bar{Y} - kS \tag{3}$$

where $\bar{Y}$ is the sample mean and S is the sample standard deviation. In this study, p and γ are set to 5% and 75%, respectively. Dixon and Massey (1969) provided methods to estimate the tolerance factor k. In this study, k is estimated from the inverse cumulative distribution function of the non-central t distribution:

$$k = \frac{t_{\gamma, N-1, \delta}}{\sqrt{N}} \tag{4}$$

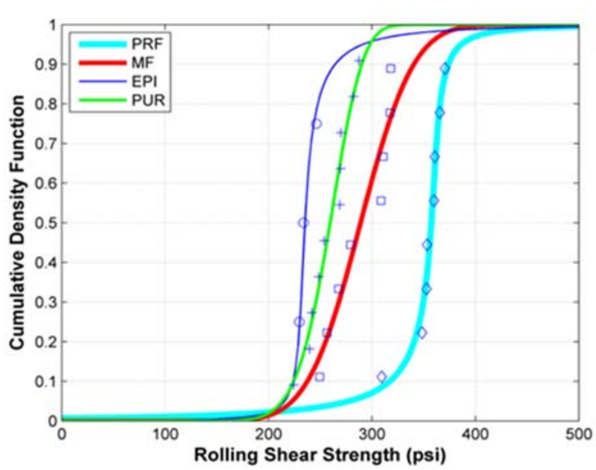
$$\delta = Z_p \sqrt{N} \tag{5}$$

Where δ is the non-centrality parameter used in the non-central t distribution, N is the sample size, Z_p is the Z value for a proportion of p (i.e. 5%) in the standard normal space. The Z_p value for each test group was obtained from the fitted distributions shown in Figure 11. The final computed characteristic rolling shear strengths for major and minor axes are summarized in Tables 6. According to Table 1 in PRG-320, the minimum characteristic value for rolling shear of Southern Pine CLT with ‘V3’ layup is 180 psi for both the major and minor axes. The PUR specimens met and exceeded the 180 psi requirement for both the major and minor axes, while only the major axis rolling shear strengths of the MF and PRF specimens passed the PRG-320 criteria.

CONCLUSIONS

Based on the above results and discussion, the following conclusions can be made:

1) All four adhesives (MF, PRF, EPI and PUR) can be used to manufacture Southern Pine CLT panels that meet the minimum characteristic rolling shear



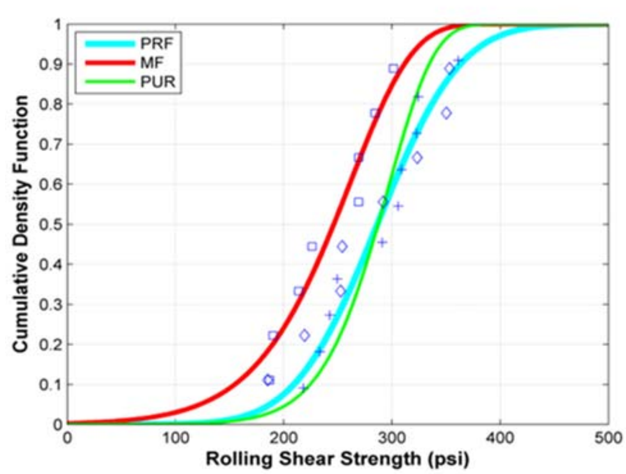


Figure 11. Fitted Cumulative Distributions Functions for Major Axis (left) and Minor Axis (right) Rolling Shear Test Data

Table 6. Characteristic Rolling Shear Strengths for Major Axis Specimens

Adhesive Type	Major Axis			Minor Axis			
	δ	Z	Characteristic Strength (psi)	δ	t	k	Characteristic Strength (psi)
MF	2.19	-2.19	201.1	4.65	6.19	2.19	146.4
PRF	2.19	-2.19	243.8	4.65	6.19	2.19	144.2
EPI	2.10	-2.10	190.4	--	--	--	--
PUR	1.91	-1.91	198.7	5.20	6.65	2.10	182.7

strengths (lower 5th percentile value with a 75% confidence interval) in the major axis direction for the 'V3' layout in PRG-320 (APA 2012).

2) Among the four adhesives, the EPI exhibited the lowest major axis rolling shear strength. Several CLT specimens made with EPI adhesive showed pre-mature delamination at the glue lines between layers. This failure mechanism significantly decreased the rolling shear strength. To use EPI for manufacturing SP CLT, further investigation such as varying the EPI spread rate or pressing cycle should be carried.

3) In the minor axis direction, only the panels made with PUR adhesive passed the PRG-320 requirement. While the MF and PRF specimens did not pass the PRG-320 minor axis rolling shear requirement, it is anticipated that modifying other parameters in the manufacturing process of SP CLT such as varying the adhesive spread rate, lumber grade, annual ring orientation, platen pressure, and/or layer thickness may resolve the minor axis rolling shear requirement for these three adhesives.

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