Report for NCSU Residential Cross Laminated Timber Panel Project (RCLT)- Proving Cross Laminated Timber Panels for Residential Homes

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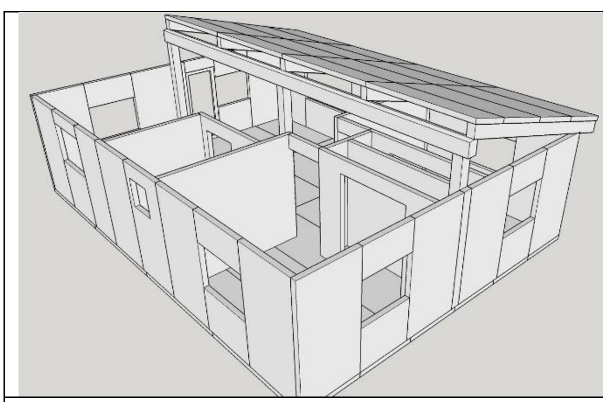
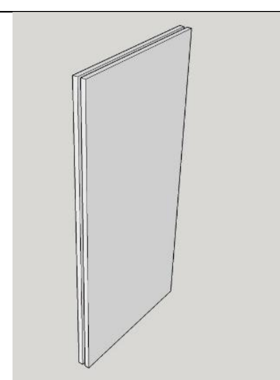


Example RCLT Home with Partial Roof Removal



Basic RCLT Panel-three ply with center spline groove

Notices-USDA & USFS

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Table of Contents

Project Goal-Proving Residential Cross Laminated Timber Panels for Residential Homes

Introduction-the US Forest Service through the Wood Education and Resource Center of Princeton, WV annually awards grants to promote production and marketing of wood products in the US. In 2018 the Wood Products Innovation Grant #18-DG-11083150-003 was awarded the Wood Products Extension Department at NCSU the grant for Proving Cross Laminated Timber Panels for Residential Homes. This concept involved producing CLT panels that are of three-ply construction with a standard size of 4-1/8x48x96” in size. The team working on the grant at NCSU WPE included Phil Mitchell, Head Principal Investigator, and Harry Watt and Frederik Laleicke, as Co-PIs. The project as submitted for a two and half year time period, but due to the policies of shutdowns of the Corona Virus, we asked for time extensions until September 2022 that were granted.

Residential CLT or RCLT, panels are three plies of 2x6”x8’ yellow pine lumber produced in the US South with the core layer at 90 degrees to the face and back. The purpose of the project is to prove that small Cross Laminated Panels or CLTs could be produced using batch cold presses that were used by the US domestic furniture industry that could produce suitable residential sized CLT panels, stack pressing of up to ten panels per cycle. Thus, a typical furniture era cold press can generate approximately 320 square feet of these panels in one cycle that may be an hour long. Such a press cycles could produce 2240 square feet in seven cycles and 2560 square feet in eight cycles in a shift. The adhesive and processing cycle times are variable, thus the output can vary with the specific equipment and adhesive used.

RCLT panels weigh approximately four hundred pounds each when made of Southern yellow pine at twelve percent moisture content oven dry basis. Individual panels at the home site are lifted into place for walls, floors and roof panels by the typical rental boom lifts used by residential construction crews. Each CLT panel has a groove sawn in at the factory for a plywood spline that is the jointing device by the construction crew using screws or nails.

All dimensional cutting is performed at the factory, so the assembly crew does not have to cut any panel for assembly. Designers select the roof joist and floor beam systems with the three-ply RCLT panels able to span up to 12’ according to current US building code and the US CLT Handbook. Thus using the standard 4-1/8x48x96” residential CLT panel, spans at the full eight feet of its length less the overlap of the rafters and joists widths. US residential building codes specify that CLTs are suitable for residential homes that meet the ASTM PRG 320 standard.

This project operated with a “hands on” format where multiple trails were made by the project staff by stack pressing CLT panels and then testing them for strength as required by ASTM PRG 320. Several adhesives by multiple manufacturers were investigated. Many wood products industry businesses provided time on their presses, so different types of presses and brands were used.

A review of potential manufacturing processes was conducted with the economical scale found to be a process of planning, automated layup and adhesive application, three cold presses, two trim and groove saws and a sliding table saw for recutting panels. Due to the long press cycle in the cold press, having multiple presses is the feasible configuration to balance layup and panel sizing times of the crew with the press cycle.

Project goals:

- Develop a small factory strategy to profitably manufacture residential CLT panels for home walls, floors and roofs using furniture era surplus equipment for pressing and trimming
- Support the develop a market for lower grade and small diameter yellow pine that could from forest thinnings for improved forest health and fire hazard reduction
- Evaluate the strength of residential RCLT panels made during the project using the ASTM PRG 320 as the standard used in the US residential building code
- Evaluate the economics of a residential RCLT

Types of Homes for the US Housing Industry

There is an acknowledged shortage of affordable housing in the US and the RCLT concept offers both affordability and fast construction using a renewable resource seen by the public as “green”. Given the flexibility of home design using RCLTs and the small size of assembly crew needed, it is likely that the RCLT concept will catch on as an additional residential construction method.

1) <u>Custom homes</u>-RCLTs are easily used to make custom homes assemble quickly and offer many design options not possible with traditional house design materials. The great ability to use greater span roof rafters and floor joists (RCLTs can span 12’) allows for designs with fewer roof rafters and floor joists. RCLT panels can work well in custom timberframe and log homes. The ability to have easy to construct cantilever designs with the 4-1/8” thick panels offers designers new elements and fast construction. Custom home designers can use RCLTs for walls, floors and roof decks and in conjunction with stick construction for hybrid designs.

2) <u>Single family home projects</u>-RCLTs are specifically useful in affordable home projects where multiple homes of similar designs are used. The simplicity of designs with repeating features offers affordability whether building one floor or multiple floor project homes, detached or attached.

3) <u>Affordable housing for farm and low income workers</u>-it is possible to reach affordability goals for farm worker and low income worker housing using RCLT housing. These homes typically use lower square footages per person as a driver for affordability and RCLTs offer lots of support for quality living in small square footage homes. RCLTs have the ability with two and three story construction to assist affordability.

4) <u>Multiple family housing</u>-RCLTs work well in stackable and linkable housing designs, with the wooden floors offers the construction crews easy access through the floor for electrical, plumbing and HVAC that steel decks covered with concrete do not.

5) <u>Disaster relief housing</u>-given that disaster relief quick housing units can be built in advance and stored in warehouses ready for immediate shipping, RCLT construction offers an affordable answer for disaster housing on quick response basis. RCLT homes can be assembled on site in a week with semi-skilled labor.

6) <u>Tiny homes</u>-while the 2x6x8 is the preferred size of lumber for RCLTs, 5/4 yellow pine lumber can also be used. A three ply 5/4x6x8 can create a three ply 3" thick panel that works well for tiny homes. Using RCLTs in a tiny home offers quick construction as the panels can be used for walls, floors and roofs. The ability to leave space for doors and windows offers great economies of scale for multiple units and standard models.

7) <u>Export opportunities</u>-locating a RCLT factory at one of the US South ports offers a great opportunity for exporting RCLT homes. The homes can be custom or made in standard models that are dead packed into shipping containers and sent anywhere in the world. In the Caribbean, these homes would offer significant hurricane resistance as well as quick construction. RCLT homes can be built on piers thus eliminating much of the cost and time of pouring concrete in a continuous foundation, a solution for sloping sites. RCLTs offer protection from small arms fire so there is a benefit to the military with RCLT construction.

Basic RCLT Construction Concepts

<u>Concepts for RCLT Walls</u>-walls for residential homes using RCLTs involve using plywood splines to connect the panels held by wood screws or nails. Openings for windows and doors are open spaces between panels and not cutouts as occur with large format CLTs. The compression loads on walls are easily handled by the RCLTs as the panels sit on one another except for windows and doors where the vertical loads are transferred through the side connections. During the lumber shorting process ahead of the planer, boards are graded into faces, backs and cores. Faces are the most attractive, cores sorted for boards that have two full faces (little wane), and backs is where boards with wane are used with the wane facing outside.

<u>Concepts for RCLT Floors</u>-floors in the RCLT system are supported by joists, floor trusses, and floor I-beams as required by the house design. The floor joist spacing can be as much as much as 12' the specifications of the US CLT Handbook for three ply CLTs. Wooden screws that connect the panels to joists are installed using impact tools with screws with self-starting threads that avoid predrilling.

<u>Concepts for RCLT Roof Decks</u>-The roof spacing of rafters and beams for the roof deck can be as long as 12 feet based on CLT standards for yellow pine lumber for the three-ply 4-1/8" thickness panels. The bottom surfaces can be exposed and care in the factory to select more attractive boards can be made from standard lumber #2 grade. RCLT panels exposed for cathedral ceilings and the floors of second story decks offer enhanced style. Wooden screws that connect the panels to joists are installed using impact tools with screws with self-starting threads to avoid predrilling.

Management

<u>Comparison of Business Strategy for RCLT Business Versus Large Scale CLT Business</u>-it is important to note the problems that large CLT factories have regarding affordability for residential CLT homes. The problem is one of high overhead costs per square foot of production due to the high capital costs of the large format CLT panels.

Large scale CLT factories produce panels that are typically twelve feet wide by sixty feet long by with options from three plus plies thick. In public announcements of new large format CLT plants, typically the investment budget is noted at $100 million +. Given the high capital costs for large panel factories and the fact that the capital costs have to be allocated over the production of the plant, the cost for residential construction is far greater than conventional construction using the large CLT factory format. The price premium for large panel CLT used in residential homes results in limited use by the residential home industry and only in the custom high $ per sf homes. It has been reported that the cost for residential home CLT panels run in the $15+ range per square foot. One major expense is the long CNC cutout and drilling equipment needed to bore assembly homes and cutouts for doors and windows. These cutouts also reduce the yield of lumber that goes into the panels.

This project's work projected that a RCLT panels may be produced at $8 per sf in the small factory format, if so, can be competitive with stick construction, but making a faster-to-assemble home with less waste of wood and other materials. This could allow residential CLT panels to be used in affordable homes, multi-family home projects and vacation homes. It is also possible to use RCLT panels to assemble smaller homes in a factory, then truck to home sites.

In the early stages of the development of a business niche for batch-pressed RCLTs, there should be a good number of used furniture-era presses available that help to make the initial operations affordable. Over time as these presses are put into service it will become more attractive to have an equipment manufacturer construct new presses. While a used press refurbished may be found in the range of $30,000 to $50,000, a new press of the same capabilities may run $150,000 to $200,000. New presses may have advantages as they can be constructed to better match the needs of RCLTs where the furniture era-presses were never intended to make RCLTs.

Alternatively, it is possible to build new CLT presses that are larger than 4x8' in size and then recut panels to needed dimensions. This method is a costlier method in equipment for the layoup and adhesive system and sawing system, and but could have economies of scale in production and sales to be able to meet the $8 per sf target for affordability.

RCLT panel factory format producing panels for residential homes-RCLT panel factories can operate in the following manner:

1. Lumber receiving and storage (receiving the standard 19% mc SYP)
2. Sticking for kiln drying
3. Kiln drying to 12% moisture content oven-dried basis when buying 19% mc lumber
4. Desticking, inspection, sorting into faces, cores and backs
5. Knife planing two faces to 1-3/8" thickness, within one day of pressing
6. Primer for isocyanate adhesives, prime within six hours of pressing
7. Chopping to length center ply boards, cutting out defects
8. Stack preparation-face and center boards
9. Layup with adhesive applied
10. Pressing
11. Trimming and grooving standard rectangular panels 4x8'
12. Cutting back for smaller panels and angle panels
13. Quality control testing
14. Packing, warehousing, shipping

<u>RCLT Manufacturing Capital Requirements Versus Large Panel CLT Manufacturing Facilities</u>-the economical configuration for a RCLT factory is with three cold presses. The space required for a RCLT factory is small when compared to that of a large panel CLT plant that reports indicate require over $100

million of invested capital. For a startup RCLT plant the option to lease factory space is likely a better business decision over building a factory.

A three-press operation could operate in a 30,000 sf weatherized building with outdoor sheds. The building has to have heat in the cooler months for the adhesives to work properly as well as a humidity control system in the winter months to add moisture to maintain the 12% EMC conditions.

An early concept in this project investigated using a robot to handle material handling of the layers of lumber and applying adhesive. This concept is possible and would involve a smaller footprint than using the separate lift and adhesive system discussed.

Production Volumes Related to Scales of Economy-Startup-a startup operation would want three presses in order to balance the work of the layup crew and the panel trimming. Three 4x8' presses could produce 160 panels per shift or 5,120 sq ft of panel at $8 per sf = $40,960 per shift and $204,800 per week, and $10,240,000 annually. One reason for the desire to have three presses in operation in a manual layup configuration is to keep the adhesive flowing due to having adhesives that react quickly to air or have a catalyst as part of the formula.

Equipment RCLT Versus Large Panel CLT Plants-RCLT operations require the equipment listed above that would total about $1 million to $2 million depending upon the configuration, whether leasing or building facilities, and the ability to find used equipment at reasonable prices, while large panel CLT factories are reported to cost in the order of $100 million. In order to be able to bring CLT residential homes to market at affordable prices, the business must find the economies of scale in all areas of the business-purchasing, equipment, employee productivity, design, production and assembly on site.

Employee Requirements-naturally it takes a good crew to consistently make quality RCLT panels, especially in a mixed manual and automated operation. The beauty of the RCLT operation is that the presses only make a 4x8' panel day after day as the primary product. A saw cutup system to make the panel angle and reduced rectangular cuts for door and window headers and footers. While some automation is possible, the operation is largely manual in the RCLT format, with employees needed for yard and kiln operations, running the planer and chop saw, stacking lumber for the automated handling system, loading stacks of panels in and out of the presses, operating the two trim saws, resizing panels and warehouse operations. Additionally there are needs for management, maintenance and quality control. It is possible to operate a RCLT factory with three presses and automated layup with from 15 to 20 employees, depending upon the level of automation.

Residential CLTs made from veneer and plywood in the Southeastern US-it may be possible to make residential CLTs using veneers and plywood made in the US South. The challenge with making CLTs with veneers is that plywood markets are generally short on veneer output, such that prices of veneers are higher per cubic foot than #2 Southern yellow pine lumber. The availability of surplus veneers in the Southern yellow pine market is not adequate for the needs of a RCLT factory given the high consumption of wood by CLT products. Given the very high cost of creating a new plywood mill, it is unlikely that our industry will see a pine veneer version of a RCLT factory.

Forestry

Place for residential CLT manufacturing in scheme of good forest management-Southern yellow pine in the US South grow fast and are grow in pure and mixed stands such that many loggers specialize in logging only Southern yellow pine.

1. RCLTs utilize small diameter yellow pine lumber-the Southern US from Virginia to Texas hosts the large yellow pine forest belt that is one of the world's largest wood baskets. Note that a third of the forest volume in North America is found in the US Southeast forest region. Yellow pine is a fast-growing softwood species that can be grown in natural forests and in plantations. Thinning practices are needed for optimal yellow pine tree growth, resulting in a large volume of small trees that can produce the lower grade 2x6s needed for residential CLTs. Sawmills report that logs as small as 11" in diameter will generate #2 grade 2x6"x8' lumber.

2. Residential CLTs utilize lower grade yellow pine lumber-the building code specifies that CLTs can use #2 grade yellow pine (SYP). This grade is considered a lower grade by the softwood lumber and construction industries. The 8' length of the #2 grade is very economical and is typically shown around $400 to $500 per kiln dried mbf, lower than any competing wood species approved for CLTs. It is known that approximately eighty percent of the sawn SYP volume grades out #2 Common and better.

3. Yellow pine volumes in the forest are high and growing per USFS statistics. USFS timber surveys for North Carolina show about 45 billion board feet of standing loblolly pine in our forests that grade F3 logs and better. Other Southern states also have high volumes of Southern yellow pine and growth rates exceed removals at this time.

4. Creating markets for materials needing to be removed from forests to improve forest health can be utilized in residential CLTs-residential CLTs offer a strong market due to the high volume of lumber needed for CLTs. Each 4x8' panel requires twenty-seven boards at 240 board feet at a 90% yield factor. A three-press RCLT operation working on a 40-hour workweek could consume 192,000 board feet of low grade yellow pine weekly, or about a dozen tractor trailer loads of lumber worth $186,000 to sawmills in the yellow pine region at $450 per thousand board feet. As a practical matter, a RCLT factory making 8' long panels would need to buy 12' and 16' lumber as 8' boards are not the targets for the market and pine logs are typically logged in tree lengths in the Coastal Plains and flat upland forests.

Species Suitable for Residential CLTs-many software species are approved for CLTs in the US but none offers the economy and wide distribution of Southern yellow pine. Yellow pine has a greater than 1.0 growth to removal rate, thus considered a fast growing renewable species.

Lumber Issues

Lumber Production Issues-there are two sawmill configurations of the production of yellow pine lumber that align well for making RCLTs:

1. Large Scale Industrial Forestry and Sawmill Operations-there are multiple large-scale yellow pine sawmill operations in the Southern US that produce large volumes of #2 grade 8 to 16' long boards suitable for making RCLTs. These mills may receive a hundred plus truckloads of logs per day and

typically operate at daily volumes greater than 50,000 board feet per hour of production. It is expected that these large industrial sawmills will be find the CLT market a major part of their production mix in the coming years.

2. Small Scale Local Forestry and Sawmill Operations-it is possible that local small-scale forestry and sawmill operations can work cooperatively to produce lumber for a RCLT plant. In fact, a group of small sawmills could own a RCLT plant and supply it with lumber, offering the mill owners the potential of being profitable on the sale of lumber and RCLT panels.

Lumber Quality Issues-the #2 grade is best suited for RCLTs given its stable price over time (other than the Covid spike period), low cost, good working properties in the factory and sufficient strength for walls, floors and roof panels. For RCLTs it is possible to use the #3 grade for cores but for simplicity of running the factory, the small savings in lumber price for #3 over #2 is small, so for practically it is better to buy only #2 for faces, backs and cores. Number 1 grade for faces can benefit the factory with less issues with knots, wane and open holes that complicate sorting and material handling.

Marketing

RCLT Industry Potential for US Housing-it is expected that a three-press RCLT operation producing one thousand square foot homes would have an annual capacity of about 300 homes per year. This concept suits itself to serving a regional market for affordable homes in multiple unit projects where there is sufficient market for a RCLT factory to be successful serving builders and project nearby. Given that the RCLT factory can be streamlined and be repeated like a rubber stamp over a wide parts of the US, this format can be successful in addressing affordable housing use a renewable resource that has a large standing inventory in the US South and has the ability to generate usable sawlogs in twenty-five years.

1. Custom homes-RCLTs panels can be used to make custom homes assemble quickly and offer many design options not possible with traditional house design materials. The great ability to use greater span roof rafters and floor joists (RCLTs can span 12') between rafters and joists allows for designs with fewer roof rafters and floor joists. RCLT panels can work well in custom timberframe and log homes for roof and floor decks. The ability to have easy to construct cantilever designs with the 4-1/8" thick panels offers designers new elements and fast construction. Custom home designers can use RCLTs for walls, floors and roof decks and in conjunction with stick construction for hybrid designs. To keep a RCLT factory focused on producing to its potential, custom homes would not be a good match unless basic panels are sent to a secondary custom home provider that could take the time to work with builders and owners needed for custom homes.

2. Single-family home projects-RCLTs are specifically useful in affordable home projects where multiple homes of similar designs are used. The simplicity of designs with repeating features offers affordability whether building one floor or multiple floor project homes detached or attached. Homes can offer upgrade options at low costs with cathedral ceilings, exposed ceilings and walls seen as desirable home features.

3. Affordable housing for farm and low income workers-it is possible to reach affordability goals for farm worker and low-income worker housing using RCLT construction. These homes typically have lower square footages per person as a driver for affordability. RCLTs have the ability with two and three story construction of assist affordability efforts. Affordability projects

using RCLT construction offers the sharing of design costs when using models that can be used in multiple projects.

4. Multiple family housing-RCLTs work well in stackable and linkable housing designs and with the wooden floors offer the construction crews easy access through the floor for electrical, plumbing and HVAC elements that steel decks covered with concrete do not. It is possible to use CLT floors in steel post and beam construction that is a faster and more economical building method as reported by an architect involved in school construction projects.

5. Disaster relief and mobile military housing-given that disaster relief quick housing units can be built in advance and stored in warehouses ready for immediate shipping, RCLT construction offers an affordable answer for disaster housing on quick response basis. The military can find the RCLT concept beneficial by RCLT panels offering some protection from battlefield attacks and having the ability to dismantle structures for additional uses, including new configurations.

6. Tiny homes-while the 2x6x8 is the preferred size of lumber for RCLTs, 5/4 yellow pine lumber can also be used. Three-ply 5/4x6x8 boards can create three-ply 3" thick panels that works well for tiny homes. Using RCLTs in a tiny home offers quick construction as the panels can be used for walls, floors and roofs. The ability to leave space for doors and windows offers great economies of scale for custom units and standard models that can be assembled in a few days, faster than with stick construction.

7. Export opportunities-locating RCLT factories at US South ports offers a great opportunity for exporting RCLT homes. The homes can be custom or made in standard models that are dead packed into shipping containers and sent anywhere in the world. In the Caribbean, these homes would offer significant hurricane resistance as well as quick construction with the ability to be transported with small trucks and trailers. RCLT homes can be built on piers thus eliminating much of the cost and time of pouring concrete in a continuous foundation when on steep slopes.

RCLT Home Designs-RCLTs make residential home design easy with lots of options for style, function and affordability. The 4x8' size of the panel results in the elimination of cutouts for doors and windows, thus offering economy in the need for production equipment and greater productivity in the factory. Door and window openings are openings left in the assembly of the panels that are the rough size openings required by the specified doors and windows. Home footprints that fall on the 4' module are most efficient. Sizing doors and windows such that factory sizing of panels on the foot supports efficient use of panels.

Types of homes-many types of homes are suitable for RCLTs:

1. Single-family assembled on site-the main target home type for RCLT construction
2. Multi-family assembled on site-can assemble on site homes of up to three stories high and units connected by common walls
3. Factory-assembled small single-family homes-assembled homes at the factory and delivered on modular home type trailers-some limitations on home size but offers fast installation at the home site
4. Tiny homes on trailers-fast assembly in the factory that can use permanent trailers for future mobility

Residential Single Family-RCLTs lend themselves to projects where there are a group of standard designs that offer economy and quick construction. The models can have options that include mirror floor plan options that offer more options with less design resources. When the designs are modular on four-foot increments, the standard 4x8' panels offer easy pathway from design to completed project.

If one wanted to offer luxury or custom construction with RCLTs, then a satellite processing operation could be set up with a sliding table saw that could modify the standard 4x8' panel into the panels needed for custom construction. One business strategy would be for the manufacturer of RCLT panels to sell them to an independent business that would design and build RCLT homes in locations different from the manufacturer. This option would be the better for the RCLT panel manufacturer given the need for production of panels and the limits of design time for custom homes.

Government and non-profits can warehouse RCLT home kits ahead of natural disasters for rapid response of housing needs. Given a factory producing kit model homes is the likely the best business strategy versus custom RCLT homes. With standard models it is possible to warehouse homes as the warehouse space for RCLT homes is small relative to their assembled on site size.

Multi-Family RCLT Construction-it is possible to utilize RCLT construction for multiple family construction by designing homes from duplexes to up to three-story common wall construction. This type of construction can service senior citizen housing, homeless housing, military housing, lodges, hotels and low wage housing.

RCLT Markets in Commercial Construction-we have been informed by commercial and institutional construction architects that RCLTs that are 12' long are desirable for floors used in school construction. Many new schools are two-stories and the CLT panels are suitable for floors in a steel post and beam design. The RCLTs have the advantage of allowing for fast installation as compared to steel decking and concrete floor decks. Additionally later modifications to the building for utilities are much easier using wooden floors than steel and concrete decking.

Permanent and temporary medical facilities can be accommodated by RCLT construction. The ability to take down and reuse RCLT structures assembled with wood screws is a great incentive by the military as well as international aid organizations and needs that are temporary in nature, like the Olympic Games. Small businesses in commercial retail establishments can find the RCLT construction desirable as the modular format serves both street front and supporting area construction. Schools and college dorm facilities can utilize the modular format of the RCLT construction to create suitable facilities to teach and house students instead of leasing mobile classrooms and dorms.

RCLTs can meet needs for quick housing in emergencies as the RCLT homes can be assembled in less than a week with prepared foundations. These houses can be stored in advance, ready for an immediate need by governmental agencies and nonprofit organizations at minimal warehousing cost.

Processing

RCLT processing operational strategies-Flow of operations for RCLTs-the flow of operations begins with the arrival of lumber that with a three-press operation making 160 panels a day, would receive about two truckloads of lumber each day. The flow of production by task is detailed below:

Dry Kiln-dry lumber from 19% to 12% oven dry basis-the incoming lumber for a three-press RCLT operation would have to dry 192,000 board feet of lumber weekly. If a two-day kiln cycle was required, then if three charges of 48,000 board feet would require a total kiln capacity of 64,000 board feet. The size of the kiln depends upon the time to dry from 19% to 12% and the volume of production that would include both time for the loading and unloading. Otherwise it may be possible with a modern sawmill with a high quality moisture detection system may be able to provide lumber in the wanted range of 12% +/- 3%, thus could avoid the need for a dry kiln at the RCLT factory.

Planing-plane two faces from 1-1/2" to 1-3/8"-it takes approximately 240 board feet of rough lumber at a 90% yield factor to make a RCLT panel that is 4x8'. In the three-press operation making 160 panels a day, it would result for a double head planer to plane 38,400 lineal feet of lumber a shift. If one used a moulder for performing the S2S work, it would need to run faster than 100 lineal feet per minute. If a planer was used and several boards were planed at the same time, the feed speed would be lower.

Chopping Lumber for Cores and Defecting-one third of the lumber consumed by RCLTS is chopped at 4' lengths for the cross way center layer of the RCLT. The incoming lumber is 97" long, so with a ¼" sawkerf the expected length of the center ply is 48-3/8" long. For the three press operation, the number of total boards per shift is 1,600 2x6x8 boards for faces, cores and backs. A simple manual upcut chop saw could be used to cut out defects in boards that have defects as well as the cores. Automation could be used for grading, but given the scale of the RCLT factory, it is likely to be capital cost prohibitive.

Adhesive Application and Layup-adhesives for CLTs are generally difficult to use in US production operations if they are isocyanate adhesives. Isocyanate adhesives have difficult working properties as they are kicked off by moisture in the air and the wood. As a result, it takes a high level of equipment and technical expertise to manage isocyanate adhesives as well as to have a strict adherence to smooth consistent production operations and quality control procedures.

1. Roller Coating-roll coating individual boards or panels is not possible with the structural isocyanate adhesives used in CLTs.

2. Curtain Coating-works well for applying adhesives for all types of adhesives and can apply adhesive to the whole 4' wide layup. One issue is that curtain coaters prefer a continuous flow of adhesive and there is a need to run the adhesive application machine on a stop and go basis for RCLTs that makes adhesive flow challenging, especially when the adhesive flow is on a stop and go basis.

3. Spraying-spraying has the same issues as curtain coaters regarding the need to be in continuous operation unless the spray system has a robust feature not to clog during the breaks in spraying of adhesive.

Pressing-hydraulic presses that generate between 125 and 150 psi are required to make RCLTS. This project focused on used US furniture era hydraulic presses that can stack press ten RCLTs in one cycle. In the future when the RCLT industry has to manufacture new presses there will be many options available regarding press panel sizes and stack heights. The virtue of cold pressing RCLTs is the low energy requirements of cold pressing with hydraulic presses.

Used Presses-the reduction of the US casegoods furniture industry has idled a number of hydraulic cold presses, many of which have gone to the scrap yard due to the lack of a need for their capabilities. The older companies like Newman, L & L and Press Systems no longer produce cold presses.

Furniture presses were designed mainly to make veneered panels for furniture tops, sides, drawer fronts and backs. Panels were stack pressed for about forty-five minutes using PVA adhesives in most cases, but some used urea formaldehyde adhesives. The two-foot wide and wider platens could be used in series when pressing parts longer than two feet long. It was common for some of these cold presses to have a center post and have on one side the ability to press seven feet long with the other side able to press panels five feet long. The most common length of panel that could be made on most furniture industry cold presses was eight feet and only a few ten or twelve feet long presses were made.

Businesswise, 12' and 16' long presses are a great asset as it allows for improved designs for RCLT floors and roof panels. In the commercial construction of steel post and frame buildings, the floor decks when made of RCLT panels offer significant design capabilities, such as the ability to locate access holes for plumbing and electrical later as needed during the construction process. Also using RCLT panels for commercial building floors speeds up the construction process as the floors can be installed as the building goes up.

Material Handling

Material Handling of Panels From Stacks-panels have to be taken individually from the press stacks for further processing.

1. Electric lifts-the stacks of panel stock in the three feeder lines for the layup line can use the lighter capacity electric lifts. The layup line requires a lift capable of 4,000 pounds that a stack going into the press would have at ten panels per stack that is the capacity of the presses.

   Electric lifts can unload the trim saws and be useful at the sliding table saw. Panels stacked for the warehouse should be limited to six panels high due to weight considerations at the home assembly site.

2. Overhead Cable Lift System-could use an electric winch and metal fixtures to pick up the panel and relocate as needed. A frame and rail system could be used at the front end of the trim saw line if one wanted to avoid scratching panel faces and back surfaces.

3. Modern Rail Lift System for Panels-the woodworking industry now has multiple vendors that offer a panel lift and storage system that can lift up a panel and on an X-Y-Z location system move panels and restack them as needed. RCLTs at 400 pounds for a 4-1/8x48x96" would offer a challenge but such a system could perhaps have a variation that is workable to unstack press loads and restack for shipping.

4. Slider System-would use an electric lift under the stack of panels from the press and the crew would slide of the top panel onto a set of line rollers or conveyors (belt or powered rollers) that would travel down to the working height of the sawing line.

5. Forklift Material Handling-it is possible to use forklifts to move stacks of panels from one workcenter to another. A stack of ten RCLTs 8’ long is approximately 4,000 pounds, certainly within the weight limits of moderately sized forklifts.

Equipment

The five main processing operations takes a mix of standard material handling equipment, common furniture era equipment and the layout automated line that would have to be a custom equipment purchase.

Trimming for Full Sized Panels-Panel Saws-one challenge for the sawing and grooving operations is the need to complete the full sawing of each side of the panel before any grooving for the assembly splines can occur. This eliminates the use of traditional furniture industry double-end tenoners to saw and groove in one pass unless having a hogging saw of some type that does the trimming. The trim strip has to fall off or be hogged to give access for the grooving to occur whether done with a stacked dato saw set or a cutterhead. Note that a single press can produce about sixty panels per shift so the piece count for sawing and grooving is not heavy, especially if combined into a two trim saw system for the panels, lengthwise before crosswise. Given the thickness of the RCLT panels, the trimming and grooving operation moves at a slow pace. Overall, the trimming team would have about 2.5 minutes per panel for the trimming and grooving operation using a set of two double-end tenoners.

Used Sawing Equipment-the furniture and sawmill industry has a wide variety of used panel sizing equipment that could be used to square up the 4x8’ RCLT panels. Given the advised strategy of only producing 4x8’ panels at the press, it should be possible to lock the saw at the desired sizes of 48 and 96” with little adjustments required in a two machine saw system. Typically these saws are located at 90 degrees from one another with the long axis of 96” being sawn first and the cross axis of 48” being sawn last. The second saw can utilize dogs on its chains while the first saw has only downward pressure holding the panel in most situations in a flow through sawing system. It helps the first saw to have rubber feet for additional traction to hold the panes in place versus the raw steel chain and high overhead pressure. The amount of trimmed wood is not great but likely more than one would want to accomplish with hogging heads or large kerf trim saws that are found on traditional double end tenoners so measures ahead in the processing can be undertaken to reduce the width of trim strips if using standard 5x5” wide boards.

The panel production industry in plywood, OSB and particleboard may also have panel sizing equipment suitable for RCLTs. One issue for all used equipment is that few saws were designed to saw 4-1/8” stock and may not be able to accommodate the large saw sizes, approximately 20”+ diameter saws, needed to cut RCLTs. Used furniture industry double end trim equipment made in America brands include Tyler, Greenlee, Challenger, Mereen-Johnson, Jenkins and Oliver.

It is possible to size RCLTs using modern beam panel saws that have a thickness cutting capacity of 4-1/8” thickness. The issue with these beam panel saws is the slow cutting cycles given one or two operators have in sawing the panel and turning it four times to size the panel initially. Additionally there are likely size variation problems due to human fatigue and related issues. It is likely that only a one-press operation could utilize a beam panel saw for sizing panels for the rectangular cuts.

New Sawing Equipment-new panel sizing equipment can be designed and engineered in a flow through system to efficiently size and groove panels in one pass. Given the lack of need to adjust the width of the saws, new equipment may be fabricated at a more reasonable cost and be quite productive compared to equipment that has to change width dimensions often. This project was quoted $500,000 per trim saw for a new double end tenoner that could handle the tasks to trim and groove RCLT panels.

All trimming and grooving equipment should include material handling for trim waste and sawdust. The undersides of the saws should have sheet metal waste defector shields with over belt conveyors to collect and transport away waste materials such that little cleanup is required by the staff.

Trimming for Angles and Smaller Sized Panels-panels used under roof angles and at sizes less than 4x8' have to be sawn on a secondary saw. Due to the need to stagger assembly joints, there could be 20% of all panels in the walls in a house have to be recut for size needed for assembly, doors and windows and house dimensional needs. The door industry has a history of having large radial arm saws with a semi-circle swivel system to cut angles and such saws should offer a manual trimming system for cut back panels that have a square edge as well as for angles. This project was not able to find one that could cut a 4/12 pitch angle that could cut the RCLT at 4-1/8" thick. It may be that in typical residential home projects that twenty to forty percent of the panels will require trimming for angles and smaller dimensions than the standard 4x8' panel. Thus for a two press operation producing 120 panels per shift, then 24 to 48 panels would require secondary trimming. This would should be performed by one or two employees and. Roof angles at the standard 4/12 pitch are needed to be sawn at the peak of the roof as well as at the gutter if the design requires a vertical cut there. Thus, it may be that over a third of the assembled panels on a house project will not be the full size 4x8' RCLT panels, but resized panels.

Grooving Edges for Splines-grooves on the edges of RCLT panels should mainly be made on the production saw lines as part of the sawing system. After the trim edges drop off or are hogged and while being chain fed, the grooves could be made using dato saws or cutterheads. The spline is ¾" wide x the width determined by the model's structural engineer. The spline holds two adjoining panels together using wood screws or nails. The 4-1/8" panel thickness has the 3/4" width groove spline centered in the panel thickness. The spline is made from plywood or lumber and inserted at assembly of the panel to the home. Woodworks reports that splines for 3-ply RCLTs should be of ¾" thickness.

Inspection and Quality Control-ASTM PRG 320 calls for testing of CLT panels for shear, bending and glue line delamination failure. A testing machine performs the shear test by compression across the glue line vertically. Bending tests are of two types, one where panels are tested in longitudinal and transverse directions under limited pressure with deflection measurements and with bending until breaking. Delamination tests involve soaking, pressure and vacuum cycles. Testing equipment for RCLTS is thought to need a testing machine of 10,000 pounds of force. RCLT factories will need to have a strong QC and documentation program with a budget for certification and setting up of a QC department at $100,000. The QC lab will have to have a testing machine, convection oven, scales, moisture meter, pressure pot and air compressor.

Packing and Managing the Shipping of Orders-while panels through the presses should always be the standard 4x8' or longer for residential homes, orders pulled for specific projects should be loaded according to assembly needs at the site. Thus, the needs of the assembly crew must be noted in the project documents and be arranged as needed. Each panel must be properly marked so the assembly crew can match the panel to the location in the house as designed. Moving individual panels in the factory can take place after the pressing operation by several methods, including conveyor, forklift and lift.

At the end of the production line there has to be a material handling method to rebuild stacks for shipping. The customer should have options of how they want the panels stacked in regards to the assembly procedures and method of material handling. The customer may choose to have small stacks for easier material handling by skid steers and small forklifts due to a full stack for the press weighs 4,000 pounds. Stacks could have separation stickers, such as 2x4's so forks at the job site can lift off individual panels without spearing the panels when moved. Since the panels have the spline groove, a lift fixture can be used with a boom to pick up the panel safely and sit aside as needed on the factory for all panels or on site for floors and roof panels on the job site.

Equipment-used-this project focused on taking used hydraulic presses from the US furniture industry that are largely not being used today and utilize them to make residential CLT panels as well as used double end tenoners for trimming and grooving panels. The presses came in many configurations but mainly had multiple overhead platens 24" wide x 36" to 60" long. Most presses stopped at 96" wide but a few were made 120" and 144" wide. Newman and the L & L Company, both of North Carolina, made the largest number of cold presses for the furniture industry. Most presses were used to make plywood panels for casegood tops, end panels, shelves, back panels and drawer fronts. Most were batch presses that had vertical openings of about 42". Given these presses are rarely used today, they are economical to purchase but typically require some repair given most have been unused for forty years. The L & L Company of Wilkesboro and Press Systems of Greensboro are out of business, Newman no longer makes cold presses. The presses were energy efficient with hydraulic electric motors from ten to twenty horsepower.

Planers, moulders and chop saws are basic equipment that are used in most lumber processing operation. These types of equipment are universal and nothing special is needed for RCLT production. The planer should have a segmented or helical head for better knife finishes than straight knife planers. Abrasive planers using sanding belts are prohibited by ASTM PRG-320.

Equipment-new-in the near future the only new equipment needed for a RCLT factory is the lumber layup system and the adhesive system. There are no used equipment options for these the layup system as they were not done in the past.

Automation Options-automation can occur in several work areas of a RCLT operation:
1. Lumber handling and preparation-sorting lumber into faces, backs and cores
2. Stack layup and adhesive application-has to be automated beyond a one press operation
3. Connecting the planer, chop saw and a stacking machine for the layers
4. Saw trimming and grooving panels out of the press to size 4x8' with grooves

Waste Material Handling and Sales Options-the waste in a RCLT operation is primarily limited planning all boards from 1-1/2" to 1-3/8", to the waste in the chopping of boards for the center ply and to trims at the panel sizing equipment. This waste can be burned in a boiler or hot water system to heat the kiln or processed into chips for boiler fuel for other operations. The planer shavings are top quality suitable for bagging for retail sale or for animal operations. There will be some trim waste at the sliding table saw when cutting out for roof angles.

On Site Assembly

On Site Assembly-the factory produces RCLTs and packages them on pallets in the order desired by the assembly crew. The crew can use a variety of material handling devices that can include forklifts, skid steers with forks and grapple loaders with forks. At the work site the crew may work in the following manner:

1. Stage the loads in desirable locations for assembly
2. Use lifts for panels to place in desired locations for assembly
3. The foundation will have the attachment devices as specified by the home designers and engineers
4. The assembly will follow the instructions of the home designer and engineer
5. Crew starts at a corner and works out as the home design requires, connecting panels in a systematic manner using splines, screws and nails
6. Panels are offset vertically to stagger joints
7. RCLT panels have groove milled to accept ¾" plywood for splines
8. The crew uses measuring tapes and levels to properly locate the panels before attaching with splines and wood screws. The crew will watch dimensions as they are assembled for walls and floors, to adjust gaps so that when the last floor and wall panels are assembled, the correct overall dimensions of the home are correct. The roof is more forgiving as an overhang roof is recommended at either a one or two foot overhang.
9. The crew works from the foundation up until the assembly is ready for rafters, floor joists and other supports for the floors and roof panels
10. Openings for doors and windows will be temporarily braced as required for proper location and safety
11. Assembly of rafters and panels in butt joints will utilize long construction screws as noted by the engineer. The rafters sit in pockets in the walls where they are connected to the wall by construction screws through the walls into the rafters.
12. Bracing will be added as needed to ensure proper assembly and safety
13. Metal strapping for wind and earthquake resistance are installed as specified by the engineer
14. Upon assembly the crew will install house wrap materials as needed, then foam board or spray foam insulation
15. Siding is installed on wooden lumber strips that are screwed to the RCLT panels by wide head screws at intervals recommended by the physical engineer

It is expected that a small crew can assemble the RCLT panels in two to three days using a common rental lift that is capable of lifting the 400 pounds of a common RCLT panel.

Adhesives and Testing RCLT Panels Made in Trials

Adhesive requirements and working properties-note that this section on adhesives is submitted by Phil Mitchell:

The standard PRG 320 requirements for CLT manufacturing in the United States that the "adhesives used in CLT shall meet the requirements of ANSI 405 with the following exceptions:

- Section 2.1.6 of ANSI 405 is not required, and
- The CSA 0177 small-scale flame test (Sections 2.1.7 and 3.7 of ANSI 405) shall be conducted using CLT specimens of the same size and geometry as the structural glued laminated timber specimens."

ANSI 405 describes the tests and performance criteria required of samples removed from CLT panels manufactured using the adhesive. In other words, the adhesive is not specified per se, but only its performance when incorporated in the CLT panel.

Adhesives Used in this Study-three vendors provided adhesive. To date, we were able to use two adhesives and their respective primer or catalyst to make CLT panels. Henkel provided Loctite HB X452 Purbond adhesive which is a polyurethane having a basis of isocyanate prepolymer. We plan to test an additional adhesive produced by Tailored Adhesives of Hickory, NC in the near future.

Structural adhesives have very high quality property requirements and tight quality control needs during the production or RCLT panels. Declared application areas are manufacture of engineered wood products, finger jointing, and face gluing. Product properties include flame resistance, resistance to weak alkalis, acids and solvents, and good flow properties. In laminating face joints, the adhesive has a maximum assembly time of 45 minutes and a minimal press time of 112 minutes at 68°F, 65% relative humidity, and 12% wood moisture content. The recommended application rate is from 27 to 37 pounds per 1,000 ft^2.

Henkel Adhesives of Bridgewater, NJ provide HB X452 Purbond adhesive for this project. When face bonding with Loctite HB X452 Purbond, it is required to pre-treat the planed surfaces of both mating components with Loctite PR 3105 Purbond primer solution at a rate of 2 grams/ ft^2. The recommended press force when manufacturing CLT with this Henkel adhesive and primer is 80 to 120 psi.

Franklin Adhesives provided Advantage EP-950A which is an acrylic-based emulsion polymer isocyanate system (EPI). Stated product properties include excellent water, heat and solvent resistance, low foam development, and use in cold and hot press applications. It exceeds the requirements of ANSI 405 and is used in many structural applications. Franklin advised that successful results had been achieved with a total assembly time of 20 minutes and a minimal press time of at least 30 minutes at 68°F, 50% relative humidity, and 12% wood moisture content. The recommended application rate is from 72 to 79 pounds per 1,000 ft^2. Advantage EP-950A requires mixing with Hardener 200 resin at a ratio of 100 parts resin to 15 parts Hardener by weight or 6.45 parts resin to one part hardener by volume. The recommended press force when manufacturing pine CLT with this Franklin adhesive system is 100 to 150 psi.

Trial	Location	Adhesive	Number Panels	Issue Summary
1	Columbia Panel, High Point, NC	Henkel Loctite HB X452 Purbond	Eight	Primer not used (arrived late) Variable feed speed of lumber through applicator-manual feed. Variable rate of glue out of extruder resulting in insufficient adhesive applied. Used a diaphragm pump. Factory temperature below recommended limits, adhesive drum stored on site in advance of pressing. Thermal strip on drum did not work for additional heat. Lumber was abrasive planed two days prior to gluing instead of using a knife planer.

2	Columbia Panel, High Point, NC	Henkel Loctite HB X452 Purbond	Zero	Moulder problems took excessive time. Extra time handling lumber when applying the primer. Problems with the pump. Time ran out with having to stop before pressing.
3	Columbia Panel, High Point, NC	Henkel Loctite HB X452 Purbond	Eight	Flat tire on truck delayed getting lumber to CP. Solicited help from AirPower to get the pump working because we had adhesive setting up in the diaphragm pump from earlier pressing. Two of these panels consisted of lumber planed the day before. Other panels had been planed 2 months before (Trail 2) and used as filler for the press. Primer was applied to the lumber planed the day before. It was not applied to the lumber planed 2 months prior.
4	Columbia Forest Products, Chatham, VA	Franklin Advantage EP-950A emulsion polymer isocyanate	Seven	Lumber was planed at NCSU the day prior to pressing. Adhesive and catalyst were mixed at the plant and applied using paint rollers in a heavy spread.
4A	Specialty Woodworks	Franklin Advantage EP-950A emulsion polymer isocyanate	Five	Two inch lumber was obtained and resawn to 1 inch lumber. Lumber was planed in SC to ¾" and 5/8"the day before pressing . An air pod press was used that could only achieve 80 psi max. We used the resulting panels for test procedure practice.
5	NC State Univ, Raleigh, NC	Franklin Advantage EP-950A emulsion polymer isocyanate	Two (deemed not good and used as platform for future trials).	Dead stack load of lumber was built too high. Because the stack was too high we had to take off the top layer of the CLT panel. Roll case height was too low such that the stack reaching the press was too low to clear press edge. Lowest layer of MDF (on the rollers) was too flexible resulting in unloading problems, used paint rollers for applying adhesive.
6	NC State Univ, Raleigh, NC	Franklin Advantage EP-950A emulsion polymer isocyanate	Three	Panels labeled: NCSU 1-1, NCSU 1-2 NCSU 1-3. Used paint rollers for applying adhesive.
7	NC State Univ, Raleigh, NC	Henkel Loctite HB X452 Purbond	Two	Use of the Prominent pump. The amount of glue applied likely less than needed due to extruder problems, though we did achieve some squeeze

				out. Used a drill pump that worked well. Panels: NCSU 2-1 and NCSU 2-2
8	NC State Univ, Raleigh, NC	Henkel Loctite HB X452 Purbond	Zero	Problem with pipe extruder, resulted in irregular flow from the adhesive applicator. No panels were made. Used a drill pump that worked well.
9	NC State Univ, Raleigh, NC	Tailored Adhesives Uraseal MC 1005	Two	New design on extruder worked well, did not have the adhesive heated sufficiently (65 degrees F), will test to determine strength values (trial 1-28-2023)

Overall the problems using an extruder that was of poor design caused the application of adhesive to be not smooth and uniform as needed, but in a hit-and-miss pattern, this occurred in Trials from 1 to 8. For Trail 9 we created a new design that reduced the extruder diameter from ¾" to 3/8". This reduction of extruder diameter allowed a uniform flow of adhesive that we considered successful. We use a series of 1/8" holes the width of the 5.5" wide boards. We did struggle with the amount of flow that was less than desired due to the adhesive being colder than wanted at 65 degrees F. We will be testing these panels at a later date.

The NCSU team has plans to perform as many as three additional trails with adhesive from Henkel Adhesives and Franklin International in 2023 with an improved extruder.

Testing of panel requirements based on meeting Standard PRG 320-Frederik Laleicke was responsible for testing our RCLT panels and provided the results and commentary:

Sample Extraction and Testing
Two batches of samples were prepared from panels made in a furniture plant in High Point (**HP**) and panels made in a plywood mill in Danville Virginia (**VA**). Panels were cut according to the prepanel qualification cutting diagram in PRG320 by Schilling, using their cut-up equipment. Samples were brought to Hodges Wood Products Lab at NC State University and stored indoors for several weeks. Two panels from the HP trial were tested by Timber Products Inspection (**TPI**). Their test report is attached.

Shear Stiffness and Shear Strength/Capacity testing could not be conducted due to technical difficulties. However, the TPI report does include these results for two of the HP samples.

Flatwise Bending Moment - Major Strength Direction
Testing was conducted using an MTS machine with a 300 kN load cell. A third-point load method was used according to ASTM D4761 Section 8.
Sample dimensions: 12 x 96 inches
HP: 5 samples
VA: 14 samples

High Point (HP)		
Specimen ID	**FbS (lbf-ft/ft of width)**	**MC (%)**

h1-6	12545.7	10.4
h1-5	8376.4	10.8
h1-7	11500.2	10.7
h1-6	13831.7	10.7
h1-5	13797.7	11.6
Average	**12010**	
Standard Deviation	**2013**	
PRG 320 V3	**1,740**	

Table 1: High Point Flatwise Bending Moment Results in Major Strength Direction

Virginia (VA)		
Specimen ID	**FbS (lbf-ft/ft of width)**	**MC (%)**
v1-7	21048.0	12.0
v1-6	15636.4	11.5
V1-5	15815.6	11.1
v1-7	19313.3	11.4
v1-5	16544.2	11.6
v1-6B	16416.6	11.2
v1-5B	17402.0	11.8
v1-6C	17762.2	11.5
v1-7B	16030.7	12.0
v1-6D	20414.5	11.7
v1-7C	16256.4	12.1
v1-5C	19364.4	11.1
v1-7D	15936.6	11.6
v1-5D	20273.7	11.9

Average	**17730**	
Standard Deviation	**1879**	
PRG 320 V3	**1,740**	

Table 2: Virginia Flatwise Bending Moment Results in Major Strength Direction

Flatwise Bending Moment - Minor Strength Direction

Sample dimensions: 12 x 48 inches

HP: 12 samples

VA: 9 samples

High Point (HP)		
Specimen ID	**FbS (lbf-ft/ft of width)**	**MC (%)**
h2-3-short-1	1951.2	10.3
h2-3-short-2	2362.2	10.4
h2-4-short-1	3111.8	10.7
h2-3-short-3	3458.1	10.4
h2-4-short-2	3111.8	10.9
h2-3-short-4	3458.1	10.8
h2-2-short-1	2763.8	10.7
h2-4-short-3	2905.4	10.4
h2-3-short-5	3027.0	10.8
h2-2-short-2	2222.2	10.7
h2-2-short-3	2772.5	10.9
h2-4-short-4	1612.1	10.8
Average	**2729.7**	
Standard Deviation	**557.0**	
PRG 320 V3	**140**	

Table 3: High Point Flatwise Bending Moment Results in Minor Strength Direction

Virginia (VA)		
Specimen ID	**FbS (lbf-ft/ft of width)**	**MC**
v2-3-short-1	2707.8	**11.0**
v2-2-short-1	3400.4	**10.7**
v2-4-short-1	5090.5	**10.8**
v2-4-short-2	3587.7	**10.8**
v2-2-short-2	3208.3	**10.3**
v2-4-short-3	3587.7	**11.0**
v2-2-short-3	3535.3	**10.3**
v2-3-short-2	2758.7	**11.0**
v2-2-short-4	3437.8	**10.3**
Average	3479.4	
Standard Deviation	**651.4**	
PRG 320 V3	**140**	

Table 4: Virginia Flatwise Bending Moment Results in Minor Strength Direction

Effective Flatwise Bending Stiffness - Major Direction
Sample dimensions: 12 x 96 inches
HP: 5 samples
VA: 14 samples

High Point (HP)		
Specimen ID	**EI (10^6 lbf-in^2/ft)**	**MC (%)**
h1-6	56.9	10.4
h1-5	61.8	10.8
h1-7	63.2	10.7
H1-6	77.0	10.7
h1-5	62.2	11.6
Average	**64.2**	

Standard Deviation	**6.7**	
PRG 320 V3	**95**	

Table 5: High Point Flatwise Bending Stiffness Results in Major Strength Direction

Virginia (VA)		
Specimen ID	**EI (10^6 lbf-in^2/ft)**	**MC**
v1-7	110.7	12.0
v1-6	94.9	11.5
v1-5	85.5	11.1
v1-7	102.9	11.4
v1-5	101.1	11.6
v1-6B	105.8	11.2
v1-5B	103.7	11.8
v1-6C	90.9	11.5
v1-7B	94.6	12.0
v1-6D	94.7	11.7
v1-7C	96.8	12.1
v1-5C	95.0	11.1
v1-7D	103.9	11.6
v1-5D	97.0	11.9
Average	**98.4**	
Standard Deviation	**6.3**	
PRG 320 V3	**95**	

Table 6: Virginia Flatwise Bending Stiffness Results in Major Strength Direction

Effective Flatwise Bending Stiffness - Minor Direction
Sample dimensions: 12 x 48 inches
HP: 12 samples, VA: 9 samples

High Point (HP)	
Specimen ID	**EI (10^6 lbf-in^2/ft)**
h2-3-short-1	9.2
h2-3-short-2	11.2
h2-4-short-1	14.8
h2-3-short-3	16.6
h2-4-short-2	14.8
h2-3-short-4	16.6
h2-2-short-1	13.2
h2-4-short-3	13.5
h2-3-short-5	14.4
h2-2-short-2	10.5
h2-2-short-3	13.3
h2-4-short-4	7.3
Average	**13.0**
Standard Deviation	**2.73**
PRG 320 V3	**3.4**

Table 7: High Point Flatwise Bending Stiffness Results in Minor Strength Direction

Virginia (VA)	
Specimen ID	**EI (10^6 lbf-in^2/ft)**
v2-3-short-1	2.4
v2-2-short-1	16.2
v2-4-short-1	24.1
v2-4-short-2	17.3
v2-2-short-2	8.8

v2-4-short-3	17.3
v2-2-short-3	16.8
v2-3-short-2	13.1
v1-2-short-1	16.3
Average	**14.7**
Standard Deviation	**5.7**
PRG 320 V3	**3.4**

Table 8: Virginia Flatwise Bending Stiffness Results in Minor Strength Direction

Block Shear Test Results
Three block shear specimens were extracted from each of the 18" x 24" samples. A total of 12 specimens were derived from four samples and two panels for the VA CLT. 24 specimens were derived from eight samples and four panels for the HP CLT. The amount of wood failure was determined using a transparent sheet with a small mesh pattern.

Virginia (VA)					
Specimen ID	**Width (in)**	**Length (in)**	**Max load (lbf)**	**Shear (psi)**	**Wood Failure (%)**
v2-6a-1	1.5	1.333	1049.887	525	73.6
v2-6b-1	1.485	1.339	2636.938	1326	89.6
v2-6c-1	1.494	1.327	754.859	381	82.6
v2-6a-2	1.487	1.434	1681.6	789	100.0
v2-6b-2	1.5	1.367	825.777	403	100.0
v2-6c-2	1.496	1.375	1033.418	502	89.6
v2-10a-1	1.496	1.392	1983.446	952	100.0
v2-10b-1	1.501	1.421	962.208	451	0.0
v2-10c-1	1.49	1.35	999.72	497	56.0
v2-10a-2	1.503	1.381	1023.918	493	100.0
v2-10b-2	1.49	1.301	1364.366	704	100.0
v2-10c-2	1.494	1.337	987.839	495	100.0

Average				626	82.6

Table 9: Virginia Block Shear Results

High Point (HP)					
Specimen ID	Width (in)	Length (in)	Max load (lbf)	Shear (psi)	Wood Failure (%)
h2-6a-1	1.502	1.264	1104.07	582	100.0
h2-6b-1	1.485	1.207	38.167	21	0.0
h2-6c-1	1.494	1.24	1176.185	635	100.0
h2-6a-2	1.506	1.278	1343.759	698	91.7
h2-6b-2	1.5	1.224	891.125	485	100.0
h2-6c-2	1.496	1.24	477.596	257	33.3
h2-6a-3	1.494	1.313	679.14	346	100.0
h2-6b-3	1.494	1.484	910.63	411	100.0
h2-6c-3	1.501	1.462	1267.519	578	100.0
h2-6a-4	1.504	1.4	988.689	470	75.0
h2-6b-4	1.501	1.433	144.946	67	0.0
h2-6c-4	1.494	1.459	1226.863	563	100.0
h2-10a-1	1.498	1.348	1467.682	727	100.0
h2-10b-1	1.507	1.3	1083.109	553	100.0
h2-10c-1	1.495	1.3	2312.227	1190	0.0
h2-10a-2	1.485	1.42	648.31	307	10.4
h2-10b-2	1.499	1.497	1198.436	534	0.0
h2-10c-2	1.481	1.466	1922.14	885	39.6
h2-10a-3	1.492	1.397	1454.382	698	76.4
h2-10b-3	1.494	1.32	1238.7	628	64.6
h2-10c-3	1.496	1.392	1045.461	502	86.8

h2-10a-4	1.493	1.44	967.02	450	50.0
h2-10b-4	1.489	1.38	1277.819	622	91.7
h2-10c-4	1.487	1.425	1204.903	569	56.9
Average				**532**	**66**
Standard Deviation				**237.4**	**38.2**

Table 10: High Point Block Shear Results

Delamination
Three 3” x 3” delamination test specimens were extracted from each of the 18” x 24” samples. Four samples had been derived from 2 VA panels (3 and 1), resulting in a total of 12 specimens.
A total of 24 3” x 3” delamination test specimens were extracted from eight 18” x 24” samples. These samples had been derived from 4 HP panels. Testing was conducted in accordance with PRG 320 -19 Section 8.2.6 “Cyclic Delamination Test”.

Virginia (VA)						
Panel ID	Specimen	Initial Weight (g)	Final Weight (g)	Total Bondline Length (in.)	Total Delam Length (in.)	Delamination (%)
1	v2-6a-1	333	323.36	24	13.25	55.2
	v2-6b-1	327	311.48	24	1.5	6.3
	v2-6c-1	306	286.95	24	0	0.0
	v2-6a-2	331	311.88	24	0.75	3.1
	v2-6b-2	328	313.13	24	3.25	13.5
	v2-6c-2	310	291.29	24	0.25	1.0
	v2-10a-1	312	293.43	24	0	0.0
	v2-10b-1	316	294.59	24	8.25	34.4
	v2-10c-1	296	286.45	24	8.5	35.4
2	v2-10a-2	332	318.58	24	0	0.0
	v2-10b-2	319	301.23	24	5.75	24.0
	v2-10c-2	344	328.46	24	0	0.0
Average						**14.4**

Table 11: Virginia Delamination Results

High Point (HP)						
Panel ID	Specimen	Initial Weight (g)	Final Weight (g)	Total Bondline Length (in.)	Total delam Length (in.)	Delamination (%)
1	h2-6a-1	333	323.36	24	0.5	2.1
	h2-6b-1	327	311.48	24	0	0.0
	h2-6c-1	306	286.95	24	3.75	15.6
	h2-6a-2	331	311.88	25	2	8.0
	h2-6b-2	328	313.13	24	0.4	1.7
	h2-6c-2	310	291.29	26	0.5	1.9
2	h2-6a-3	312	293.43	24	0	0.0
	h2-6b-3	316	294.59	27	7.7	28.5
	h2-6c-3	296	286.45	24	7	29.2
	h2-6a-4	332	318.58	28	0	0.0
	h2-6b-4	319	301.23	24	0.75	3.1
	h2-6c-4	344	328.46	29	13.5	46.6
3	h2-10a-1	326	304.25	24	0	0.0
	h2-10b-1	314	293.5	30	2	6.7
	h2-10c-1	353	332.29	24	2.1	8.8
	h2-10a-2	278	256.36	31	2	6.5
	h2-10b-2	313	287.82	24	0	0.0
	h2-10c-2	272	257.93	32	0	0.0
4	h2-10a-3	306	286.47	24	0	0.0
	h2-10b-3	329	315.26	33	1	3.0
	h2-10c-3	330	308.58	24	0	0.0
	h2-10a-4	259	243.44	34	0.8	2.4

	h2-10b-4	262	248.06	24	1.4	5.8
	h2-10c-4	329	320.85	35	5.7	16.3
Average						**7.8**

Table 12: High Point Delamination Results

Discussion of Results
According to PRG 320 the corresponding CLT grade is V3. All panels passed the requirements for flatwise bending moment in the major and minor direction (see Tables 1 – 4). The HP panels did not pass the bending stiffness test in the major direction (Table 5), which the VA panels did (Table 6). Bending stiffness in the minor direction was sufficient for both batches of panels (Tables 7 and 8).

Block shear testing and the resulting amount of wood failure criteria could not be met (Tables 9 and 10). For HP the average amount of wood failure was 66 % and only 62.5 % (95 % required) of the samples (15 out of 25) were above the wood failure minimum of 60 %. The average amount of wood failure for the VA samples was 82.6 %. 83 % of the samples (10 out of 12) were above the minimum wood failure of 60 %, thus not meeting the requirement of 95 %.

The delamination test was not passed by either the VA or HP samples (Tables 11 and 12). It has to be pointed out that after soaking and before measuring the delamination, the samples were dried beyond the suggested 110 - 115 % of their original weight. The additional dimensional shrinking increases the amount of delamination.

Early in the project we sent two panels to Timber Products Inspection of GA that tested the panels for shear, delamination and bending per the PRG 320 Standard. These panels had mixed success in meeting the strength standards due to issues with the adhesive extruder.

Architects and Builders

Working with architects on residential CLT designs-this project was greatly assisted by the Asheville CLT architect, Crawford Murphy. He offered significant assistance regarding the view of an architect towards the utilization of the RCLT concept to producing a series of modular model and custom homes. Brian Newman of Kitty Hawk provided helpful insight as a builder/developer.

Exhibiting at Industry Events

Exhibiting at industry events-we performed a large number of onsite events where we shared the RCLT concept with a wide variety of forest and wood products industry professionals, as well as builders and developers. Some of these events included:

1. North Carolina Home Builders Expo-we did exhibit our CLT panel construction methods for residential home to builders and supporting members of the NC Home Builders Association in September 2019, 2021 and 2022.
2. Carolina Loggers Association-we did have an exhibit booth at the 2022 Annual Meeting in Wilmington, NC where we promoted RCLT's place in the forest industry.

3. North Carolina Forestry Association-we attended at the NC Forestry Association Meeting in Wilmington in 2020 and discussed RCLT to members.
4. International Woodworking Fair-we hosted a booth at the IWF 2020 in Atlanta with CLT samples.
5. Regional NC Marketing Project Meetings-we presented samples and discussed the RCLT project at the 30+ regional meeting across North Carolina as part of our Wood Innovations marketing project that operated from 2019 through 2022.
6. North Carolina Statewide Marketing Team Grant-we hosted over thirty on site regional meetings promoting NC forest and wood products as part of a general statewide marketing Wood Innovations grant. At each meeting we presented samples of CLT and performed “show and tell” about RCLT concepts. We did host a public RCLT project workshop on the campus of NCSU on August 11, 2022.

Industry Assistance List

Assistance of industry in the project-supplied lumber, adhesive, equipment and advice:

1. Aiken Controls-Lenoir, NC
2. Air Power-High Point, NC
3. Associated Hardwoods-Granite Falls, NC
4. Bill Mills Cabinets-Statesville, NC
5. Brian Newman Properties-Kitty Hawk, NC
6. Burns Wood Products-Hudson, NC
7. Cameron Lumber-Cameron, SC
8. Chrisco Machinery, Liberty, NC
9. CLT Lite-Asheville, NC
10. Columbia Forest Products-NC and VA
11. Columbia Panel-High Point, NC
12. Culp Lumber-New London, NC
13. Deal Metal Manufacturing/Minda-Granite Falls, NC
14. Franklin International-Louisville, KY
15. Henkel Adhesives-Bridgewater, NJ
16. Jolin –Hickory, NC
17. Jordan Lumber-Mt. Gilead, NC
18. KDS Dry Kilns-Etowah, NC
19. Kiln-Direct-Burgaw, NC
20. Locke-Lane Construction-Stony Point, NC
21. McShan Lumber-McShan, MS
22. MDS2 Architects-Asheville, NC
23. North Carolina Forest Service-Raleigh, NC
24. North Carolina Forestry Association-Raleigh, NC
25. North Carolina Home Builders Association-Raleigh, NC
26. Professional Builders-NJ
27. Purple Heart Homes-Statesville, NC
28. Roy Wood Consulting, Boulder, CO
29. Shaver Wood Products-Cleveland, NC
30. Specialty Millwork-Lexington, SC
31. Tailored Adhesives-Hickory, NC
32. Timber Products Inspection-Conyers, GA
33. Windy Ridge-VA
34. Wood Products Group International-Lenoir, NC
35. Woodworks-DC