WCTE 2014 Quebec City Canada August 10-14
World Conference on Timber Engineering

Development of Southern Pine Cross-Laminated Timber for Building Code Acceptance

Daniel Hindman[1] and John Bouldin[2]

ABSTRACT: The current interest and growth of cross laminated timber (CLT) products has spurred interest in the manufacture of CLTs in the United States. The purpose of this paper is to explore the development of CLT materials from southern pine lumber commonly available in Virginia. A 5-layer CLT panel has been constructed using No. 2 southern pine lumber. Evaluation of mechanical properties, fire performance and acoustical performance were conducted. Results of these evaluations can guide the development and acceptance of CLT products in the International Building Code. Mechanical properties were considered acceptable except for cyclic delamination. Fire properties demonstrated an increased charring rate compared to solid wood, with evidence of layer delamination. Acoustic properties produced acceptable STC ratings, but IIC ratings did not meet the building code levels. The challenge of eliminating delamination of southern pine CLT layers appears to be the largest hurdle towards building code acceptance of this product.

KEYWORDS: Cross-Laminated Timber, CLT, Southern Pine, Mechanical Properties, Fire Testing, Acoustic, Vibration

1 INTRODUCTION

Interest in the use of cross-laminated timber (CLT) products has increased in the United States, as evidenced by recent publication of a product standard, ANSI/APA PRG 320 *Standard for Performance-Rated Cross-Laminated Timber* (PRG 320) [1] and the production of a United States version of the *CLT Handbook* [2], originally published in Canada [3].

While the sustainable aspects of CLT have been well established compared to competitive products, there is a desire to increase the manufacture of CLTs as a regional practice, accessible through many green building systems in the United States. The Leadership in Energy and Environmental Design (LEED) suite of green building certification systems recognizes a regional material credit, intended to "increase demand for building materials and products that are extracted and manufactured within the region, thereby supporting the use of indigenous resources and reducing the environmental impacts resulting from transportation."[4]

Currently, in Virginia and the Southeastern United States, southern pine lumber represents the dominant wood resource available. The southern pine lumber group consists of loblolly pine (*Pinus taeda*), longleaf pine (*Pinus palustris*), shortleaf pine (*Pinus echinata*) and slash pine (*Pinus elliottii*) [5]. With the downturn in the United States housing market, many landowners have been examining other options for using southern pine lumber in forest products. While the housing market is starting to rebound, there is also pressure from trees damaged by the southern pine beetle to bring these products to harvest soon [6].

The purpose of this project was to measure the properties of southern pine CLT product to meet the requirements of the 2012 *International Building Code* (IBC) to allow use in the United States building market [7]. In cooperation with the Southern Virginia Higher Education Center, a series of CLT panels southern pine lumber were manufactured. These panels were tested for mechanical strength, fire resistance, and acoustic performance. Results of this testing would provide information crucial to the development of a southern pine CLT building product to the building code requirements in the United States.

2 LITERATURE REVIEW

Compliance with the IBC requires product testing for three different characteristics: structural strength, fire resistance and acoustic properties.

2.1 Mechanical Properties

The strength of CLTs is discussed in PRG-320 [1]. PRG 320 defines standard requirements for manufacturing, performance and qualification testing of CLTs. Seven different grades of CLT materials are defined based on the

[1] Daniel Hindman, Virginia Tech University, 1650 Research Center Dr. Blacksburg, VA 24061. Email: dhindman@vt.edu.

[2] John Bouldin, Virginia Tech University, 1650 Research Center Dr. Blacksburg, VA 24061. Email: johnbouldin@vt.edu.

use of visual or mechanical graded lumber and species group.

The construction methods for the manufacture of CLT panels are also specified in PRG 320 [1]. Boards oriented in the parallel direction (strong axis) must have a net width of at least 1.75 times the lamination thickness, and boards oriented in the perpendicular direction (weak axis) must have a net width of 3.5 times the lamination thickness unless the boards are edge glued. Adhesives used must comply with AITC 405 *Standard for Adhesives Used in Structural Glued Laminated Timber* except for Section 2.1.6 [8], and shall be evaluated for heat performance per Section 6.1.3.4 of DCO PS1 *Structural Plywood* [9]. The moisture content of all lumber during fabrication must be 12 % ± 3%, and the moisture content must be greater than or equal to 8% at the time of testing [1].

PRG 320 also specifies the testing methods used for evaluation of bending and shear properties of CLT panels. Bending specimens should have a width of 30.5 cm with a center-to-center span of 30 times the panel depth [1]. Bending tests are to be conducted using third-point loading flatwise to the top ply as specified in ASTM D 198 *Standard Test Methods of Static Testing of Lumber in Structural Sizes* [10]. The bending strength characteristic value should be determined by ASTM D 2915 *Standard Practice for Sampling and Data-Analysis for Structural Wood and Wood-Based Products* [11] methods and multiplied by a factor of 2.1 for comparison to grade property values given in PRG 320 [1]. The average bending stiffness is used for comparison to PRG 320 [1] table values.

Shear specimens should have a width of 30.5 cm with a center-to-center span of five to six times the panel depth [1]. A center point loading is applied to the panel flatwise a specified in ASTM D 198 [10] for shear property determination. The shear strength characteristic value should be determined by ASTM D 2915 [11] methods and multiplied by a factor of 3.15. At the current time, shear strength values specific to CLT grades have not been assigned.

Other tests for adhesive-related properties are also specified in PRG 320 (ANSI/APA 2012), including ANSI/AITC A190.1-2007 *Structural Glue Laminated Timber* (ANSI/AITC 2007), which specifies the use of test standard AITC T107 *Shear Test* (AITC 2007a) for bondline shear evaluation, and AITC T110 *Cyclic Delamination Test* (AITC 2007b) for assessing face delamination of adhesive bonds between the CLT layers.

Kim et al (2013) measured the bondline shear strength of CLT composed of red pine (Pinus densiflora) with a polyurethane adhesive against the Korean glulam standard. The test methods used were similar in approach to AITC T107 (AITC 2007a), although the acceptance values differed. Kim et al. [15] measured a shear strength of 3.5 MPa, and 90.3% wood failure for red pine CLT layers.

2.2 Fire Resistance

Fire resistance in the IBC is defined in Chapter 6 specifies building types based upon fire resistance [7]. Type I and II construction are composed of all non-combustible materials. Type III may have some combustible – but fire-treated – materials. Type IV construction is reserved for heavy timber, where the time for a timber to burn through is longer than conventional stick framing. Type V construction includes combustible materials used in construction – including light-frame wood framing.

At the current time, CLT construction in the United States is classified as Type V [16], but expectations are to change this classification to Type IV due to the similarities between mass timber and heavy timber construction [2]. According to 602.4, Type IV construction must have exterior walls which meet a fire rating of 2 hours or more [7]. Fire ratings are achieved by the use of ASTM E 119 [17] or other similar methods.

2.3 Acoustical Performance

Acoustic properties of buildings are specified for building elements that separate dwelling units. Chapter 1207 addresses sound transmission and provides two requirements for sound [7]. For air-borne sound, all walls, floors and ceilings shall have a sound transmission class (STC) of 50 or more when tested with ASTM E 90 [7,18]. For structure-borne sound, floor and ceilings shall have an impact insulation class (IIC) rating of 50 when tested with ASTM E 492 [7,19].

2.4 Summary of Building Code Acceptance Criteria

For a southern pine CLT panel to be considered acceptable by the building code the panel must:

a) Conform to the grades specified in ANSI/APA PRG-320 [1]
b) Meet a 2 hour fire rating using ASTM E 119 [17] or similar evaluation method
c) Meet an STC of 50 (wall / floor) using ASTM E 90 [18] and an IIC of 50 (floor) using ASTM E 492 [19]

3 MATERIALS AND METHODS

3.1 CLT Panel Manufacture

A set of 5-layer CLT panels were manufactured using nominal 2x4 (38.1 mm x 88.9 mm) No.2 southern pine lumber. Lumber was surfaced planed before manufacture to a thickness of 35 mm. A polyurethane adhesive obtained from a local supplier was used for fabrication of all panels. Each layer was edge glued for ease of fabrication. Layers were fly cut on a CNC table in lieu of planing. Final panel thickness was 175 mm. Panel sizes were dictated by the particular test methods described.

3.2 Mechanical Property Evaluation

3.2.1 Bending Strength and Stiffness

PRG-320 recommends a bending and shear testing of panel sections using various spans of a flatwise bending test [1]. All samples were 305 mm wide. Sample size for characterization of bending properties was a beam with a length to height ratio of 30:1. A span of 4.73 m was used, producing a length to height ratio of 27.0:1. Bending tests used a third-point loading arrangement, where loads were applied 1.57 m from the support (Figure 1) by an MTS universal testing machine with an integrated 222 kN load cell (± 1% sensitivity). A constant displacement rate of 6.35 mm/min was used. A yoke supported by screws attached at the supports was used to suspend an LVDT for deflection measurement. Beams were tested until failure. Load and center point deflection data were continuously recorded throughout the test.

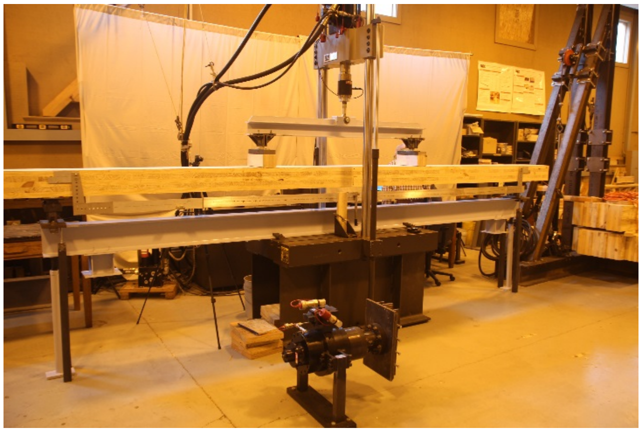

Figure 1. *Bending Testing of CLT Panel Section*

The maximum length of CLT sections which could be produced was 2.43 m long. To create the bending samples, three sections of CLT were joined together using a multiple lap joint connection. The connection was cut on the CNC router and then the connection was re-pressed with polyurethane adhesive. After the testing of the first specimen, bending failure was observed at the joint. Subsequent bending samples were reinforced with a series of ASSY VG CYL 8 mm diameter x 160 mm long screws placed perpendicular to the laminations and ASSY VG CYL 8 mm diameter x 240 mm long screws placed at a 45 degree angle.

After bending tests were conducted, specimens were extracted for moisture content and specific gravity according to ASTM D 4442 [20] and ASTM D 2395 [21], respectively.

3.2.2 Shear Strength

After testing the 5.49 m long bending specimens, a 1.22 m long undamaged section was cut from each sample for shear testing. None of the shear specimens contained any splice joints. ASTM D 198 (ASTM 2013a) procedures were used for shear testing. Originally, a width of 30.5 cm and a span of 1.07 m were used for shear testing with a span-to-depth ratio of 6.1:1, while PRG 320 recommends a span-to-depth ratio of 5 to 6:1 (ANSI/APA 2012). However, due to the failure loads approaching the 222 kN limit of the universal testing machine, many of the samples were reduced to 22.9 cm wide.

A center point loading of the specimens was applied using an MTS universal testing machine with an integrated 222 kN load cell (± 1% sensitivity). Two yokes, one on each side, were supported at the neutral axis over the supports to measure the neutral axis midspan deflection using two LVDTs (± 25.4 mm range, ± 0.25% sensitivity). A displacement rate of 1.27 mm per minute was used. Maximum load was used for shear strength calculations.

Figure 2. *Shear Testing of CLT Panel Section*

3.2.3 Bondline Shear Strength

The bondline shear strength test applied a shear force at the bondline of a stepped specimen cut from the bending specimens previously tested. The test is conducted with the load oriented parallel to grain of the entire specimen [13]. However, CLT bondlines present both a parallel to grain and perpendicular to grain surface at every bond interface. AITC T107 [13] procedures are a reasonable test standard when applied to glued laminated timbers, where cross-laminations are not present. For uniformity of testing, all bondline shear test specimens were placed in the testing machine with the parallel to grain lamination being held upright in the fixture, while the perpendicular to grain lamination was loaded. This orientation was the same as used by Kim et al. [15].

Three bondline shear samples were cut from each of the four bondlines in each of the 10 test specimens for a total of 120 bondline shear test specimens. The shear area for the specimens measured approximately 4.44 cm by 5.08 cm, and testing was conducted based on ASTM D 143 Standard Test Methods for Small Clear Specimens of Timber [22]. The displacement rate was 0.61 mm per minute. All specimens were loaded until failure and the ultimate load was recorded.

3.2.4 Cyclic Delamination

AITC T110 [14] describes the method to assess the delamination of bonded wood composites. As stated previously for AITC 107 [13], the cyclic delamination test assumes that all laminations are in the parallel to grain direction, while CLT bondlines contain a parallel to grain, and a perpendicular to grain lamination at each bondline. One full-depth sample measuring 76.2 mm by 76.2 mm by 174.6 mm was cut from each of the 10 bending specimens. Because all four faces of the CLT test specimen exhibit end grain, the length of each bondline on each face of the test specimens was measured, rather than only two end grain faces as specified in AITC T110 [14]. The samples were then weighed, submerged in water, placed in an autoclave and subjected to a vacuum of 63.5 mm of mercury for 30 minutes followed by a pressure cycle of 517 kPa for two hours. The specimens were then placed in a drying oven at 160° F until dried to within 9% to 15% of the original weight.

Due to the difference in swelling in the parallel-to-grain and perpendicular-to-grain directions during the autoclave procedure, the length of the exposed bondlines increased and the bondlines became curved, rather than remaining a straight line due to barreling of the specimen from Poisson's effect. After the autoclave and drying procedures, the total length of each expanded bondline was measured, as was the total length of bondline separation on each face for each specimen. The percentage of delamination was calculated based on the post-testing bondline lengths. Figure 4a is a photograph of the face delamination specimen after testing demonstrating the barreling from Poisson's effect. Figure 4b is a photograph of the bondline separation observed.

3.3 Fire Testing

Fire testing of CLT panels were conducted with an intermediate scale fire chamber at the Forest Products Laboratory in Madison, WI. Fire specimens were 914 mm x 914 mm and placed horizontally in a fire chamber Specimens were cased by a combination of 2x6 lumber and gypsum wall board (GWB) to a final size of 0.99m wide by 1.2 m long. A series of embedded thermocouples at different depths within the panel measured the temperature during testing. The test chamber follows a prescribed heating schedule and the range of temperatures was measured throughout the test. When the thermocouples in the center of the panel reached 300 degrees C or when three hours had elapsed, the test was ended. The 300 degrees C temperature was considered an indicator of the base of the char layer and equivalent to the reduction in cross-section to the corresponding depth.

Six different configurations of CLT panel were tested to examine the fire resistance of a number of common treatments. The six different fire test configurations are shown in Table 1. A bare panel was used to establish the baseline CLT resistance to fire. A series of panels using gypsum wall board (GWB) included a single layer, a double layer with furring strips as spacers, and a triple layer were used. Another configuration used a layer of intumescent paint (Firefree 88).

The FPL intermediate-scale horizontal furnace (Figure 3) is a metal box lined with ceramic/mineral fiber blankets and heated by eight diffusion-flame natural gas burners on the floor of the furnace. The interior dimensions of the furnace were 1.83 m long, 0.99 m wide and 1.22 m high. The ceramic fiber-lined metal cover for the furnace was removed from the top of the furnace. A test frame with the test specimen was placed on top of the furnace. Noncombustible inserts inserts were placed on each side of the 0.99 m long specimen located in the center of the frame (Figure 2). The 1.2 m dimension spanned the width of the furnace. All air for combustion was provided by natural draft through vents at the bottom of the furnace. Six capped furnace thermocouples were located 305 mm from the top of the furnace interior. The gas was controlled so temperature of the capped thermocouples followed the time–temperature curve in ASTM E119 [17]. Temperature data for the furnace and the specimen were recorded in 5 seconds intervals.

Table 1. *Configurations of CLT Panels Tested By Intermediate Scale Oven*

Sample #	Fire Treatment
Test 1	Bare CLT (control)
Test 2	Single Layer GWB
Test 3	Single Layer GWB w/Spacers
Test 4	Two Layers GWB w/Spacers
Test 5	Intumescent Coating
Test 6	Three Layers GWB

Figure 3. *CLT Specimen Being Removed from Intermediate-Scale Oven*

Thermocouples were installed within the specimens by drilling holes from the back/non-fire exposed surface (Figure 8). The thermocouples were made at FPL from 24 gauge, Type K glass insulated thermocouples wires (Omega GG-K-24). Depth of thermocouple was calculated by subtracting the depth of the hole from the 175 mm thickness of the CLT panel. Temperature readings were continuously monitored throughout the testing time.

3.4 Sound Transmission Testing

Sound transmission testing will be conducted at Architectural Testing in York, PA. Testing used ASTM E 90 [18], and ASTM E 492 (*Standard Test Method for Laboratory Measurement of Impact Sound Transmission Through Floor-Ceiling Assemblies Using the Tapping Machine*) [19].

Wall samples were 2.43 m wide by 2.43 m tall and composed of two sections of CLT panel joined with a tongue and groove joint. Floor samples were 3.02 m wide by 3.63 m long and composed of four sections of CLT panel joined with a tongue and groove joint. The joints was sealed with silicone adhesive and a set of ASSY VG CYL 8 mm diameter x 160 mm long screws were used.

Table 2. *Wall and Floor Panel Sizes Used For Acoustic Property Testing*

Sample #	Acoustic Treatment
Wall 1	Bare CLT (control)
Wall 2	CLT panel Isomax rubber isolators 2-7/8" hat channel R-13 insulation GWB w/ duct tape
Floor 1	Bare CLT (control)
Floor 2	CLT panel Isomax rubber isolators 2x8 joists R-19 insulation GWB w/duct tape

Two wall panels and two floor panels were tested as shown in Table 4. The first wall panel was a bare wall. The bare panels allowed the CLT acoustical performance to be compared to other similar materials such as concrete. The second wall had rubber Isomax resilient sound isolation clips attaching a 41.3 mm high hat channel secured over R-13 rockwool batt insulation. The hat channels were covered with 12.7 mm GWB and all edges and screw holes were sealed with duct tape (Figure 4).

The first floor panel was a bare floor (Figure 5). The second floor had rubber Isomax resilient sound insulation clips attaching 2x6 joists with R-19 rockwool batt insulation attached between. The joists were covered with 12.7 mm GWB and all edges and screw holes were sealed with duct tape.

Figure 4. *Wall 2 Prepared for STC Testing*

Figure 5. *Floor 1 Prepared for STC and IIC Testing*

4 RESULTS AND DISCUSSION

4.1 Mechanical Property Test Results

The mechanical property results of the southern pine CLT samples are shown in Table 1. For comparison, the Grade V3, using No.2 southern pine parallel members and No.3 southern pine cross-layers is shown for comparison in Table 1.

4.1.1 Bending Strength and Stiffness

The allowable bending strength and bending stiffness values were greater than the V3 grade value in PRG-320 [1]. The coefficient of variation (COV) associated with the bending strength and stiffness indicated low variability among the test samples. Screw reinforcement of the lap joints was added for the latter nine samples, and did not appear to affect the bending strength and stiffness.

Table3. Mechanical property test results

Property	Experimental SP CLT Value	PRG-320 [1] and NDS [23] Values
Bending Strength, F_bS		
Bending Stiffness, EI_{eff}	4,110 kN-m^2/m (8.8% COV)	3,900 kN-m^2/m
Allowable Shear Strength, F_vA	146 kN/m (8.3% COV)	N/A
Bondline Shear Strength	4.38 MPa (3.3% COV)	N/A
Bond Line % Wood Failure	81.6% (8.2% COV)	> 80%
Cyclic Delamination Bondline Failure	17.2% (72.9% COV)	< 5%
Moisture Content	9.8% (4.4% COV)	> 8.0%
Specific Gravity	0.55 (3.1% COV)	0.55 (NDS)

4.1.2 Shear Strength

Shear strength values from the shear test specimens are shown in Table 3. The PRG 320 standard contains no criteria for shear strength of CLT beams. These values are offered for comparison to other test methods and materials. Failure included tension failure in the lower plies, horizontal shear in the parallel plies, shear at the bondlines, and rolling shear within the cross ply layers. Most specimens exhibited a combination of these failures. Some localized crushing of the wood fibres under the loading test fixture were also observed.

4.1.3 Bondline Shear Strength

The wood failure, bondline shear strength and face delamination percentages measured from the CLT specimens and comparisons to the allowable standard values are shown in Table 3. The threshold for acceptable wood failure given in ANSI/AITC A 190.1 [12] is greater than or equal to 80% for softwoods, and the percentage of wood failure for the tested specimens was 81.6%. The majority of wood failure was observed in the cross plies, not parallel-to-grain in the strength axis plies.

Three different failures were observed in the bondline shear testing including rolling shear in the cross lamina, adhesive failure, and wood failure parallel-to-grain in the vertical strength-axis plies. Most specimens exhibited a combination of these failures across the sheared surface area. Specifically, rolling shear failure is not addressed in AITC T107 [13], since rolling shear failure is not observed in glued structural timber where all plies are oriented parallel to the strength axis of the member [24]. Both the rolling shear and parallel-to-grain shear failures were considered wood failure versus the adhesive failure. Kim et al. [15] combined the rolling shear and parallel-to-grain shear failure areas to calculate the percentage wood failure, and found similar values of percent wood failure for both parallel and perpendicular oriented specimens. At this time, it is unknown whether the differentiation of rolling shear and parallel-to-grain shear failures has an effect upon the bondline shear properties.

4.1.4 Cyclic Delamination

The percentage of delamination measured from the CLT specimens is shown in Table 3. For softwoods, AITC T110 (AITC T110 2007b) specifies that bondline delamination shall not exceed 5%, while the average delamination for the face delamination specimens was 17.3%. The variability of the delamination results was very high, with a COV of 77.3%, and face delamination values ranging from 3% to 33%. This excessive delamination may have resulted with manufacturing issues related to the moisture content of the wood at time of manufacture, which was lower than that specified by PRG 320. Further research may be needed to ensure that the face delamination of southern pine CLTs produced with the lumber moisture content meeting ANSI/APA PRG-320 corresponds with the established criteria.

4.1.5 Moisture Content and Specific Gravity

Moisture content values were above the minimum limit for testing of CLT properties specified by ANSI/APA PRG-320 [1]. The average specific gravity was equal to the specific gravity of the southern pine species group listed in the *National Design Specification for Wood Construction* [23].

4.2 Fire Resistance of CLTs

4.2.1 Charring of CLTs

The charring rates for the CLT were examined by subtracting the times of the protective membranes for 300°C on the surface of the CLT. A time of 31.2 minutes used for Test 5 with intumescent coating based on extrapolation of the data within the CLT. The results are shown in Figure 6. The measured wood thickness after the tests were consistent with the results based on the 300°C temperature data.

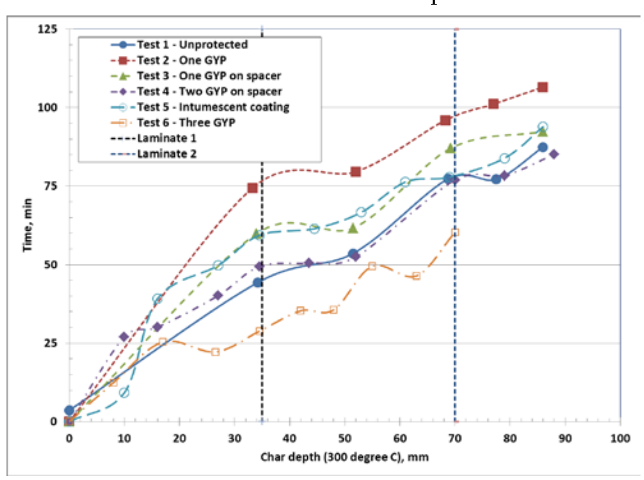

Figure 6. *Time vs. Char Depth Relationship for CLT Panels Tested*

From the curves for the 300°C measurements (Figure 6), the char rates can be expressed as two sets of linear equations: charring of the first laminate and charring after the first laminate (Table 4). Except for Test 6 (3 layers of GWB), the char rate after the first laminate (35 mm) was greater than the char rate for the first laminate. In Test 6, the char rate after 35 mm was comparable to that for the first laminate (Table 4).

Table 4. *Linear regression equations for the times to obtain 300°C, i.e. the slopes of the equations are the charring rate in minutes per mm.*

Test No.	Equation for char depth (x) of 35 mm or less, min	Equation for char depth (x) of 35 mm or greater, mm
1	t = 1.1865 x + 3.66	t = 0.8521 x + 14.61
2	t = 2.2365 x + 0.02	t = 0.6444 x + 50.57
3	t = 1.7603 x	t = 0.7161 x + 32.15
4	t = 1.4217 x + 2.42	t = 0.7291 x + 21.02
5	t = 1.7863 x - 0.01	t = 0.6488 x + 34.23
6	t = 0.8341 x + 2.58	t = 0.8295 x – 0.30

The charring rates for the first laminate after adjusting for times for surface to be 300°C were different for the six specimens (Table 4) with the rate for one layer gypsum board specimen being 2.7 times faster than the char rate for the specimen with three layers of gypsum board. The results likely reflect the continued presence of the protective membrane as the charring of the first laminate occurs. Regression of the first laminate char rate with times for 300°C at the surface of the CLT for the five samples with protective membranes resulted in an equation with an R^2 of 0.88 [m = - 0.0107 t300,surface + 2.2753, where m is char rate slope (Table 4) for first laminate]. The greater the protective membrane, the slower the char rate for the first laminate.

The charring rates (slopes) for the charring after 35 mm (first laminate) were fairly consistent for the six tests (Table 4). This likely reflects the reduced influence of the protective membrane on the charring rate. For the post 35 mm data, the average char rate for the six tests was 0.737 min./mm or 81 mm per hour which is considerably faster than the 38 mm per hour commonly assumed for wood. This likely reflected the delamination of the char layers at the glue line in these tests and the higher furnace temperatures later in the test.

4.2.2 Failures At Glue Lines

In these tests, there was consistent evidence of the delamination of the char layer at the glue lines between the first and second laminates and between the second and third laminates. In the fire test, this was observed by a sharp temperature increase for thermocouples at the interface. In Test 1 of the unprotected CLT, temperature data indicated delamination at between 2516 and 2741 seconds, average 44.0 minutes for the first laminate and between 4386 and 5131 seconds, average 77.9 minutes for the second laminate. The visual/audio observations were for char/wood delamination at 44 and 80 min. for the first and second laminates, respectively. The thermocouple data indicated that the delamination occurred at temperatures between 228°C and 367°C with an average of 282°C. In the case of the first test of the unprotected CLT, the test was continued through charring of the third laminate and observations of the specimen after the test indicate uncharred surfaces which would be consistent with delamination of the glue line at temperatures below that at which wood chars.

Figure 7. *Photograph of CLT Specimen After Fire Test. Note Unburned Sections of Panel.*

4.2.3 Potential Load levels for One, Two and Three Hours Rated Assemblies

From the experimental data, the char depths at one, two, and three hours were determined (Table 5). Using the calculation procedures discussed in the CLT Handbook [1] and the char depths of Table 5, the percentage allowable load for the observed char depths (Table 6) were calculated. Values for southern pine No. 2 lumber were used. From Table 6, the Test 6 case of three layers of GWB should obtain a rating of 2 hours based upon the intermediate furnace results. This is considerably lower than recent tests, which have found that a commercial spruce CLT with one layer of GWB was able to withstand a 2 hour fire test using ASTM E 119 [17]. The additional layers of GWB required for the southern pine CLT seem to be needed due to the delamination of the laminations and the increased charring rate.

Table 5. *Char Depths at One, Two and Three Hours Calculated from Experimental Data*

Test No.	Char Depth at One Hour	Char Depth at Two Hours	Char Depth at Three Hours
	Mm	Mm	mm
1	53.1	-	-
2	15.8	59.6	-
3	17.4	68.5	-
4	-	27	-
5	19.2	85	-
6	-	-	56.5

Table 6. *Estimated % Design Load for the Observed Char Depths (Table 9)*

Test No.	Estimated % Design Load		
	1 Hour Rating	2 Hour Rating	3 Hour Rating
1	14	-	-
2	52	14	-
3	48	14	-
4	100	27	-
5	44	11	-
6	100	100	14

4.3 Acoustical Properties of CLTs

The STC and IIC values determined from testing are shown in Table 7. The Wall 1 and Floor 1 STC values were identical, considering that these panels were the same configuration tested in vertical and horizontal directions, respectively. The use of the treatments on the wall and floor (Wall 2 and Floor 2) increased the STC value over the threshold for acceptance by the building code (STC=50).

Table 7. *STC and IIC Values of CLT Wall and Floor Sections*

Sample #	STC	IIC
Wall 1	43	-
Wall 2	54	-
Floor 1	43	27
Floor 2	56	46

The IIC value did not achieve the value of 50 as required by the IBC. However, the testing here was considered a worst-case scenario with no covering of the upper surface. This testing was done to provide flexible results rather than limit the types of floor treatments deemed acceptable. The use of a floor treatment is recommended with this CLT panel to achieve the IIC rating of 50.

5 CONCLUSIONS

This project discussed the mechanical properties, fire properties and acoustic properties of southern pine CLT materials for exploration of compliance with the International Building Code. Mechanical properties including bending strength and stiffness were greater than similar rated CLT panels from PRG 320. However, the cyclic delamination test results did not meet the appropriate AITC standards. Fire testing of panels in an intermediate scale furnace demonstrated increased charring rates compared to solid wood, possibly due to delamination of the layers. Acoustical properties of CLTs met the IBC standard for STC ratings, but did not meet the IIC rating for floor assemblies. Further assembly testing with toppings over the floor may be needed to achieve the desired IIC rating. In both the mechanical property and fire property evaluations, delamination of layers was considered a problem and must be addressed for future use of southern pine CLTs.

ACKNOWLEDGEMENTS

The authors wish to acknowledge support from the Center for Innovative Technology (CIT) as well as the help of the Center for Advanced Manufacturing and Energy Efficiency (R&D CAMEE) at the Southern Virginia Higher Education Center in South Boston, VA. Technical assistance for the acoustic properties was also provided by the staff at ATI, now Architectural Testing and Matthew Golden. Technical assistance for the fire properties was provided by the Forest Products Laboratory, specifically Dr. Robert White. Henkel, Tailored Chemical Products Inc., Firefree Coatings Inc. and Kinetics Noise Control are also acknowledged for their material support.

REFERENCES

[1] ANSI/APA: PRG 320 Standard for Performance-Rated Cross-Laminated Timber. APA – The Engineered Wood Association, Tacoma, WA, 2012.

[2] FPInnovations: CLT Handbook. Canadian Edition. 2011. SP-528E. FPInnovations. Pointe-Clair, QC, Canada.

[3] FPInnovations and Binational Softwood Lumber Council: CLT Handbook. US Edition. 2013. SP-529E. FPInnovations. Pointe-Claire, QC, Canada.

[4] USGBC: LEED Reference Guide for Green Building Design and Construction. 2009. Washington, D.C.

[5] USDA: The Southern Pines. http://www.fpl.fs.fed.us/documnts/usda/amwood/256spine.pdf. 1985. Accessed August 17, 2013.

[6] Mississippi Business Journal: Solid prices, beetles prompting timber owners to harvest. http://msbusiness.com/blog/2012/07/12/solid-prices-beetles-prompting-timber-owners-to-harvest/. 2012. Accessed August 17, 2013.

[7] International Code Council. 2012 International Building Code. International Code Council, Inc. 2012.

[8] American Institute of Timber Construction (AITC). AITC 405 Standard for Adhesives for Use in Structural Glued Laminated Timber. American Institute of Timber Construction, Centennial, OH, 2005.

[9]

[10] National Institute of Standards and Technology (NIST). Voluntary Product Standard PS 1-09 Structural Plywood. National Institute of Standards and Technology U.S. Department of Commerce. Gaithersburg, MD, 2009.
[11] American Society of Testing and Materials (ASTM). D198Standard Test Methods of Static Testing of Lumber in Structural Sizes. American Society of Testing and Materials (ASTM). West Conshohocken, PA, 2013.
[12] American Society of Testing and Materials (ASTM). D2915 Standard Practice for Sampling and Data-Analysis for Structural Wood and Wood-Based Products. American Society of Testing and Materials (ASTM). West Conshohocken, PA, 2013.
[13] ANSI/AITC. A190.1-2007 American National Standard for Wood Products, Structural Glued Laminated Timber. American Institute of Timber Construction (AITC), Centennial, CO, 2007.
[14] American Institute of Timber Construction (AITC). AITC T107 Shear Test. American Institute of Timber Construction, Centennial, OH, 2007.
[15] American Institute of Timber Construction (AITC). AITC T110 Cyclic Delamination Test. American Institute of Timber Construction, Centennial, OH, 2007.
[16] Kim, H., Oh, J., Jeong, G., Yeo, H., and Lee, J. Shear Performance of PUR Adhesive in Cross Laminating of Red Pine. Journal of Korean Wood Science and Technology. Vol 41, no. 2, pp. 158-163, 2013.
[17] North Carolina Department of Insurance (NC DOI). Cross Laminated Timber Construction. http://www.ncdoi.com/Osfm/Engineering_and_Codes/Documents/evaluations/Cross%20Laminated%20Timber%20Construction%20March%2030%202010_.pdf. Accessed April 29, 2014.
[18] American Society of Testing and Materials (ASTM). E119 Standard Test Methods for Fire Tests of Building Construction and Materials. ASTM, West Conshohocken, PA, 2013.
[19] American Society of Testing and Materials (ASTM). E 90 Standard Test Method for Laboratory Measurement of Airborne Sound Transmission Loss of Building Partitions and Elements. ASTM, West Conshohocken, PA, 2013.
[20] American Society of Testing and Materials (ASTM). E 492 Standard Test Method for Laboratory Measurement of Impact Sound Transmission Through Floor-Ceiling Assemblies Using the Tapping Machine. ASTM, West Conshohocken, PA, 2013.
[21] American Society of Testing and Materials (ASTM). D143 Standard Test Methods for Small Clear Specimens of Timber. American Society of Testing and Materials (ASTM). West Conshohocken, PA, 2013.
[22] American Wood Council (AWC). National Design Specification for Wood Construction. American Forest & Paper Association. Washington, DC, 2012.
[23] ASTM (2013c). D4442-07 Standard Test Methods for Direct Moisture Content Measurement of Wood and Wood-Base Materials. American Society of Testing and Materials (ASTM). West Conshohocken, PA.
[24] ASTM (2013d). D2395-07 Standard Test Methods for Specific Gravity of Wood and Wood-Based Materials. American Society of Testing and Materials (ASTM). West Conshohocken, PA.
[25] American Institute of Timber Construction (AITC). AITC 117 Standard Specifications for Structural Glued Laminated Timber of Softwood Species. American Institute of Timber Construction, Centennial, OH, 2004.