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QUASI-STATIC OUT-OF-PLANE TESTING OF CLT AND NLT PANELS

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CHAPTER 1 INTRODUCTION

The University of Maine (UMaine) in conjunction with WoodWorks and Karagozian & Case, Inc. (K&C) performed a testing program aimed at investigating the bending response of cross-laminated timber (CLT) and nail laminated timber (NLT) panels in their major strength direction under a uniformly-applied quasi-static load. The apparatus utilized for the testing was developed by UMaine and consisted of a series of rubber bladders filled with water capable of applying a uniform quasi-static pressure in a controlled fashion. Applied pressure, out-of-plane deflection, and total resisted load were measured and recorded as panels were displaced well beyond the deflection associated with peak panel strength. While most of the panels were tested with end conditions that did not restrain panel rotation, six were tested with connections meant to represent those that might be used to attach a wall to a floor and ceiling in a building designed to resist significant out-of-plane wall loading. Panels following testing are shown in Figure 1-1.



Figure 1-1. Panels Following Testing.

CHAPTER 2

TEST SPECIMENS

A total of 25 CLT and 6 NLT panels were tested during this effort. In general, the panels were 10'-6" long (major strength direction) and 4'-0" wide (minor strength direction), although panels that were tested with angle bracket connections were only 9'-6" in length. Different panel and connection types were tested with between three and five specimens being tested for each configuration. A test matrix documenting the different configurations tested is included as Table 2-1. Additionally, attributes of each panel tested, including panel weight, moisture content at time of testing, connection type, test date, and miscellaneous notes, are recorded in Table 2-2.

ID	Description	Ply No.	L [in]	W [in]	Qty	Bracket Horz. Leg Type Fasteners		Vert. Leg Fasteners			
V1	Gr. V1 CLT	3	126	48	5		No Connection				
5V1	Gr. V1 CLT	5	126	48	5		No Connection	1			
V1CA	Gr. V1 CLT	3	114	48	4	ABR105 (14) SD10212 (Simpson) (Simpson)		(10) SD10212 (Simpson)			
V1CB	Gr. V1 CLT	3	114	48	3	L4x4x1/4 (6) ASSY SK 5/16x4 (MyTiCon)		(6) ASSY SK 5/16x4 (MyTiCon)			
E1	Gr. E1 CLT	3	126	48	4	No Connection					
V4	Gr. V4 CLT	3	126	48	4	No Connection					
4NLT	2x4 NLT	N/A	126	48	4	No Connection					
6NLT	2x6 NLT	N/A	126	48	4		No Connection	1			

Table 2-1. Specimen Test Matrix.

Panel ID	Panel Type	Weight ¹ (lb)	Average MC ² (%)	End Cond. Type ³	Test Date	Notes
V1-1	Gr. V1, 3-ply CLT	500	13.5	S	3/1/16	Shakedown test for instrumentation
V1-2	Gr. V1, 3-ply CLT	490	14.5	S	3/9/16	Tested twice (hose detached)
V1-3	Gr. V1, 3-ply CLT	490	13.3	S	3/9/16	Small water bag rupture
V1-4	Gr. V1, 3-ply CLT	490	14.0	S	3/9/16	
V1-5	Gr. V1, 3-ply CLT	470	12.2	S	3/10/16	
5V1-1	Gr. V1, 5-ply CLT	780	17.4	S	3/11/16	Multiple tests (end rotation); stopped early due to bag leak
5V1-2	Gr. V1, 5-ply CLT	740	N/A	S	3/11/16	Bladder failed post-peak
5V1-3	Gr. V1, 5-ply CLT	920	11.5	S	4/19/16	
5V1-4	Gr. V1, 5-ply CLT	880	11.7	S	5/3/16	Tested twice (crossbar yield)
5V1-5	Gr. V1, 5-ply CLT	740	8.1	S	5/3/16	Stopped early due to bag leak
V1CA-1	Gr. V1, 3-ply CLT	440	N/A	SR-A	3/18/16	Shakedown test for "semi-rigid" test setup (end rotation); 4 brackets at each end of panel
V1CA-2	Gr. V1, 3-ply CLT	660 ⁴	7.2	SR-A	5/18/16	4 brackets at each end of panel
V1CA-3	Gr. V1, 3-ply CLT	425	7.6	SR-A	5/19/16	3 brackets at each end of panel
V1CA-4	Gr. V1, 3-ply CLT	420	7.0	SR-A	5/24/16	2 brackets at each end of panel
V1CB-1	Gr. V1, 3-ply CLT	420	7.0	SR-B	5/18/16	4 brackets at each end of panel
V1CB-2	Gr. V1, 3-ply CLT	430	8.0	SR-B	5/23/16	3 brackets at each end of panel
V1CB-3	Gr. V1, 3-ply CLT	410	7.2	SR-B	5/23/16	2 brackets at each end of panel
E1-1	Gr. E1, 3-ply CLT	480	14.5	S	3/22/16	
E1-2	Gr. E1, 3-ply CLT	480	13.3	S	3/22/16	
E1-3	Gr. E1, 3-ply CLT	480	15.5	S	3/22/16	
E1-4	Gr. E1, 3-ply CLT	470	13.4	S	3/24/16	
V4-1	Gr. V4, 3-ply CLT	400	9.2	S	8/5/16	
V4-2	Gr. V4, 3-ply CLT	410	9.2	S	8/5/16	
V4-3	Gr. V4, 3-ply CLT	395	9.9	S	8/5/16	
V4-4	Gr. V4, 3-ply CLT	405	10.6	S	8/5/16	
4NLT-1	2x4 NLT	480	7.0	S	5/9/16	
4NLT-2	2x4 NLT	500	6.9	S	5/9/16	
4NLT-3	2x4 NLT	420	6.9	S	5/10/16	
6NLT-1	2x6 NLT	680	6.5	S	5/10/16	Tested twice (nut backed off)
6NLT-2	2x6 NLT	700	6.6	S	5/17/16	
6NLT-3	2x6 NLT	660	7.2	S	5/17/16	

Table 2-2. Attributes of Individual Panels.

1

Weight measured with crane scale, reported to nearest 10 pounds. Moisture Content (MC) measured at two to five points on the panel immediately following test with Delmhorst BD-2100 2 hand held moisture meter.

3 End condition type: S: simple; SR-A: semi-rigid with Simpson bracket; SR-B: semi-rigid with L4x4x1/4 bracket.

4 Panel weighed 660 pounds with end pieces attached; panel alone not weighed.

2.1 PANEL DESCRIPTION

Three different grades of CLT were tested during this effort:

- Grade V1 panels as manufactured by DR Johnson Lumber Company. Both 3-ply and 5ply thick Grade V1 panels were tested. According to [1], Grade V1 CLT consists of No. 2 Douglas fir-Larch (DFL) lumber in the major strength direction and No. 3 DFL lumber in the minor strength direction. All Grade V1 panels were made from planed 2×8 (nominal) lumber. In general, the constituent lumber pieces did not appear to be intentionally edge glued, although adhesive was observed intermittently between boards along some edges. While the 3-ply panels had vertical finger joints that were visible on the broad face of the board in the major strength direction (see Figure 2-1), no finger joints were visible in the 5-ply panels.
- Grade E1 panels as manufactured by Nordic Structures. Only 3-ply Grade E1 panels were tested. According to [1], Grade E1 CLT consists of 1950f-1.7E Spruce-Pine-Fir (SPF) Machine Stress Rated (MSR) lumber in the major strength direction and No. 3 SPF lumber in the minor strength direction. All grade E1 panels were comprised of relatively short (i.e., approximately 2'-0" to 4'-0") segments of 2×4 (nominal) lumber in the major strength direction. No adhesive was observed between adjacent board edges. Post-test observations indicated that board segments were joined via horizontal finger joints (see Figure 2-1).
- Grade V4 panels as manufactured by SmartLam. Only 3-ply thick Grade V4 panels were tested. According to [2], Grade V4 CLT consists of No. 2 SPF (South) lumber in both the major and minor strength directions. The Grade V4 panels were visually similar to the Grade V1 panels in terms of constituent board dimensions, finger joints, and observable edge gluing.





(a) Grade V1 (Grade V4 similar). (b) Grade E1. Figure 2-1. Finger Joint Orientation in Panels.

Additionally, 2x4 and 2x6 NLT panels were tested during this effort. The NLT panels were manufactured by StructureCraft Builders, Inc. using No. 2 or better SPF. Boards were aligned broad face to broad face and nailed with two 0.121-inch diameter by 3-inch long nails at 16 inches on center. The 2x4 NLT specimens were backed by 3-ply, 4-layer 15/32-inch thick

plywood. The 2x6 NLT specimens were backed by 5-ply, 5-layer 15/32-inch thick plywood. The plywood was used as the compression face of the panels in testing.

2.2 CONNECTION DESCRIPTION

Most panels were tested without connections. The test setup in this case allowed for free rotation of the panel at its ends. This panel end condition is referred to as "simple" in this report.

A total of seven panels were tested with angle bracket connections, although the first test was a shakedown test and prompted modifications to the test setup for the remaining tests. Two types of angle brackets were used and are shown in Figure 2-2: (a) 11 gauge Simpson Strong-Tie (SST) ABR105 brackets and (b) 4.5-inch lengths of pre-drilled ASTM A36 $L4 \times 4 \times 1/4$ angle. Bracket (a) was secured using fourteen SD10212 (i.e., #10 x 2-1/2") self-drilling screws by SST in the horizontal leg (i.e., leg attached to panel) and twelve SD10212 screws in the vertical leg; both screws were manufactured by SST. Bracket (b) was secured using six ASSY SK 5/16x4 self-drilling screws by MyTiCon in each leg of the angle bracket. The number of angle brackets used was varied between tests and is indicated in Table 2-2. Angle brackets were evenly spaced along the width of the panel. To simulate an actual floor/roof that would not rotate, end supports for the angle bracket connections were cut from 5-ply Grade V1 panels. This panel end condition is referred to as "semi-rigid" in this report.

Details concerning the "simple" and "semi-rigid" end condition test setups are documented in Chapter 3.





(a) Simpson Strong-Tie ABR 105 Bracket.





(b) L4x4x1/4 Bracket. **Figure 2-2. Angle Bracket Connection Types.**

CHAPTER 3

TEST APPARATUS

As mentioned in Chapter 2, two different test setup configurations were used to apply the quasi-static uniformly applied pressure load to the CLT and NLT panels. The first configuration was used to simulate "simple" end conditions while the second configuration was used to simulate end conditions associated with platform framing of a multi-story building (i.e., referred to as the "semi-rigid" configuration). The final test setup configurations and the changes that were made during testing to each configuration are described below. Additionally, the type and layout of instrumentation is documented.

3.1 TEST SETUP

3.1.1 "Simple" Configuration

A schematic diagram of the "simple" test setup configuration is included as Figure 3-1.



Figure 3-1. Schematic Diagram of "Simple" Test Setup Configuration.

The "simple" test setup configuration consisted of two crossbars, one at each end of the panel, secured to a concrete reaction floor by eight tension rods, two at each end of each crossbar. The tension rod nuts were hand-tightened for these tests providing a pre-tension on the order of a few hundred pounds.

Several crossbars were used during the testing. The initial crossbar consisted of back-toback channels with one tension rod at each end of each crossbar. However, the force at each panel end was applied with a large enough eccentricity (i.e., with respect to the channels' shear center) to cause the channels to rotate and the tension rods to yield (see Figure 3-2). As such, the back-to-back channels were replaced with a tube with two tension rods at each end of each crossbar early in the testing program.



Figure 3-2. Failure of Initial Crossbar.

In addition, other errors associated with faulty test setup components also caused several panels to be tested more than once. These errors are documented in Table 2-2.

Prior to each test, a series of rubber bladders were placed on the concrete reaction floor directly underneath the panel. The bladders were centered on the panel and piled on top of each other in order of decreasing length (i.e., the longest was placed on the reaction floor and the shortest was placed on the top). Bladders were 3'-6", 5'-0", 5'-10", 6'-2", 7'-4" and 10'-0" long and 4'-0" wide in all circumstances. After the 10'-0" bladder burst (see test 5V1-2 in Table 2-2), it was replaced with 3'-6" and 7'-4" long bladders at the lowest level. Each bladder was encased in a woven bag to minimize outward deformation. The bladders in place prior to panel placement can be seen in Figure 3-3.



Figure 3-3. Bladders in Place Prior to Panel Placement.

Filling the bladders with water caused the panels to deflect upwards. The bladders were filled with tap water from a 3-inch diameter PVC distributor that ensured that the water in all of them had the same pressure. Pressure was measured via a pressure transducer (PT 1) at one bladder away from the water flow and with an analog meter where the hose enters the distributor. The ends were free to rotate due to a 48-inch-long, 1.25-inch-diameter steel cylindrical bar between the crossbar and the panel. The simply supported panels had a structural span of 10'-0" from roller to roller. A photograph of the final configuration for the "simple" test setup configuration is included as Figure 3-4.



Figure 3-4. "Simple" Test Setup Configuration.

3.1.2 "Semi-Rigid" Configuration

A schematic diagram of the "semi-rigid" test setup configuration is included as Figure 3-5.



Figure 3-5. Schematic Diagram of "Semi-Rigid" Test Setup Configuration.

The "semi-rigid" configuration utilized the crossbar and tension rod system of the "simple" configuration, but replaced the cylindrical bar with stub end pieces of a 5-ply CLT panel to which angle brackets were secured. The resulting span from inside of end piece to inside of end piece was 9'-6" (i.e., the length of the panel). To prevent the end pieces from sliding or rotating during testing, a steel brace was installed on the back side of the end pieces and the tension bars were wrench-tightened to provide a pretension force of between one and two thousand pounds. A photograph of the "semi-rigid" test setup configuration is included as Figure 3-6.



Figure 3-6. "Semi-Rigid" Test Setup Configuration.

For the "semi-rigid" test setup configuration, loose straps were placed over the panel and connected in a loop beneath the structural floor to restrain the panels in case of a catastrophic angle bracket failure. These restraining straps are shown in Figure 3-7. While the restraining straps applied a force to panels, this force was negligible compared to that associated with panel rupture.



Figure 3-7. Restraining Straps in "Semi-Rigid" Test Setup Configuration.

3.2 INSTRUMENTATION

A list of instrumentation used during this test program is listed in Table 3-1. Additionally, the layout of the instrumentation is shown schematically in Figure 3-8. The data recorded by all instrumentation was read during the tests with LabView through a DAQ card and written concurrently to a CSV file. For the initial tests, data was collected at a 10 Hz frequency. However, this frequency was later increased to 100 Hz. The reason for this change was to record enough data to allow for the filtering out of signal noise (i.e., typically at approximately 3.5 Hz) that was most noticeably present in the pressure data. A 50-point running average filter was used to remove this signal noise from the pressure data.

ID	Description	Make	Serial No.	Service Dates	
PT 1	50 psi pressure transducer	N/A	N/A	Pre- 3/18/16	
PT 1	30 psi pressure transducer	Omegadyne	N/A	3/18/16 onwards	
LC 1	25K washer load cell	Omega	345390	Pre- 3/30/16	
LC 1	50K pancake load cell	Interface	1220AF-50K / AS1955	4/19/16 onwards	
LC 2	20K washer load cell	Omega	345393	Pre- 3/30/16	
LC 2	50K pancake load cell	Interface	1220AF-50K / AS1976	4/19/16 onwards	
LC 3	20K washer load cell	Omega	345395	Pre- 3/30/16	
LC 3	50K pancake load cell	Interface	1220AF-50K / AS1977	4/19/16 onwards	
LC 4	20K washer load cell	Omega	345400	Pre- 3/30/16	
LC 4	50K pancake load cell	Interface	1220AF-50K / AS1978	4/19/16 onwards	
SP 1	10" string pot	Celesco	L1505710C	Entire test cycle	
SP 2	10" string pot	Celesco	L1505723C	Entire test cycle	
SP 3	10" string pot	Celesco	L1505726C	Pre- 4/26/16	
SP 3	10" string pot	Celesco	N/A	4/26/16 onwards	
SP 4	10" string pot	Celesco	L1505728C	Entire test cycle	
SP 5	25" string pot	Celesco	3113	Pre- 4/26/16	
SP 5	25" string pot	Celesco	N/A	4/26/16 onwards	
SP 6	25" string pot	Celesco	N/A	Entire test cycle	
SP 7	25" string pot	Celesco	2906	Pre- 4/26/16	
SP 7	25" string pot	Celesco	N/A	4/26/16 onwards	
SP 8	10" string pot	Celesco	L1505721C	Entire test cycle	
SP 9	10" string pot	Celesco	L1505716C	Pre- 4/26/16	
SP 9	10" string pot	Celesco	N/A	4/26/16 onwards	
SP 10	10" string pot	Celesco	L1505719C	Entire test cycle	
SP 11	10" string pot	Celesco	L1505737C	Entire test cycle	

Table 3-1.	Instrumentation	List.
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Figure 3-8. Instrumentation Key Plan.

Notes concerning the instrumentation are recorded below:

- Pressure transducer
 - Pressure in the rubber bladders was measured using one pressure transducer (PT 1) that was connected by a 1-inch diameter hose to the southwest corner of the lowest bladder.
- Load cell (see Figure 3-8 for location in plan)
 - Initially, washer load cells were used to measure the force in the tension rods. During the course of the testing program, the washer load cells were found to produce non-repeatable data. As such, washer load cells were replaced with pancake load cells for the remainder of the tests.
 - Assuming negligible tension rod pre-tension, the sum of the forces recorded by all load cells (i.e., LC 1 through LC 4) should be equal to the total pressure in the bladders, as recorded by PT 1, multiplied by the loaded area of the panel. In some cases, the PT1 and load cell sum curves are noticeably different in magnitude. The primary reason for this deviation is thought to be due to the rubber bladder not always being in contact with the entire surface area of the panel, particularly in the width direction.
- String potentiometer (see Figure 3-8 for location in plan)
 - Panel deflection was measured at eleven locations using string potentiometers (SPs) with 10-inch and 25-inch strokes. One 10-inch SP was attached at the midspan of each crossbar to measure crossbar displacement (i.e., SP 4 and SP 8). The remaining SPs were placed in a 3×3 grid centered at panel mid-span. SP 5, 6, and 7 had a 25-inch stroke and SP 1, 2, 3, 9, 10, and 11 had a 10-inch stroke.

- The string potentiometers were hung from a timber frame that was supported by legs resting directly on the concrete reaction floor. There was no connection between the test fixture and the timber frame other than the concrete floor.
- Hooks were glued to the panels and a loop at the end the string was pulled over the hook (see Figure 3-9).



Figure 3-9. Connection of String Potentiometers to Panels.

- Video / Photo
 - Two digital video cameras were used to record the tests. One was supported above the panel near the center and the other mounted on a tripod to capture the long edge of the panel. The side video recorded the edge that had the lines traced on it at 3-inches on center.
 - Still photographs were taken of the set-up and of each panel before, during, and after testing.

3.3 TEST PROCEDURE

The test procedure was the same regardless of which test setup configuration was used – panels were set in place, the fixture elements installed, plumbed, leveled, and tightened, and instrumentation attached. Data and video recording were started and then the ball valve between the hose and PVC distributor was full opened. Water pressure at the tap was between 80 and 90

psi. Panels generally reached peak bending strength within three to five minutes, but testing continued until it was apparent that no additional useful deformation data could be gathered.

Typically, one or more SP would detach during the initial violent failure, occasionally more would come off in subsequent failures, and eventually, in general, the remaining 10-inch SP would reach the end of their stroke. Testing was typically complete within ten minutes. Figure 3-10 shows a typical 3-ply CLT panel near the end of its test.



Figure 3-10. Photo of Typical 3-ply CLT Panel at End of Test.

During the testing of the 5-ply panels, flexure of the crossbars was visually evident near peak panel bending strength. This deformation was tracked by SP 4 and 8.

CHAPTER 4 TEST RESULTS

This chapter presents the results from the testing program. This first part of the chapter provides qualitative observations concerning panel out-of-plane response through failure. Photographs documenting the results of each test are included in Appendix A. The second part of the chapter describes the test data recorded by instrumentation and presents representative plots for a single test. Similar plots for all tests are included in Appendix B.

4.1 QUALITATIVE OBSERVATIONS

Table 4-1 records the observed limit state and the peak panel strength for each test. With one notable exception, all CLT panels without connections (i.e., "simple" test setup configuration) failed near panel mid-span, presumably due to flexural stress. The location of panel rupture typically centered on knots, sloped grain, and finger joints (see Figure 4-1). No shear slip between panel plies away from the location of panel rupture was observed.





(a) Sloped Grain.

(b) Finger Joint.

Figure 4-1. Typical Panel Failure Locations.

One 5-ply Grade V1 CLT panel failed in shear near the supports. Failure was initiated at a point internal to the panel, thus making it difficult to observe failure progression in time. Figure 4-2 shows photographs of the 5-ply panel that failed in shear.







Panel ID	Panel Type	Limit State Type ¹	Peak Strength ² (psi)	Residual Strength 1 ³ (psi)	Residual Strength 2 ⁴ (psi)
V1-1	Gr. V1, 3-ply CLT	F	-	-	-
V1-2	Gr. V1, 3-ply CLT	F	7.6	1.5	-
V1-3	Gr. V1, 3-ply CLT	F	6.4	1.5	-
V1-4	Gr. V1, 3-ply CLT	F	7.0	1.7	-
V1-5	Gr. V1, 3-ply CLT	F	7.5	1.8	-
5V1-1	Gr. V1, 5-ply CLT	F	-	-	-
5V1-2	Gr. V1, 5-ply CLT	F	-	-	-
5V1-3	Gr. V1, 5-ply CLT	F	13.2	7.4	2.3
5V1-4	Gr. V1, 5-ply CLT	F	18.6	6.8	3.1
5V1-5	Gr. V1, 5-ply CLT	V	13.9	6.0	-
V1CA-1	Gr. V1, 3-ply CLT	N/A	-	-	-
V1CA-2	Gr. V1, 3-ply CLT	V	7.1	4.2	-
V1CA-3	Gr. V1, 3-ply CLT	V/TB	7.5	3.7	-
V1CA-4	Gr. V1, 3-ply CLT	V/TB	6.7	4.5	-
V1CB-1	Gr. V1, 3-ply CLT	F	7.4	3.5	-
V1CB-2	Gr. V1, 3-ply CLT	F	6.5	2.8	-
V1CB-3	Gr. V1, 3-ply CLT	F/TB	7.6	2.4	-
E1-1	Gr. E1, 3-ply CLT	F	5.8	1.6	-
E1-2	Gr. E1, 3-ply CLT	F	6.3	1.2	-
E1-3	Gr. E1, 3-ply CLT	F	5.7	1.5	-
E1-4	Gr. E1, 3-ply CLT	F	7.2	1.2	-
V4-1	Gr. V4, 3-ply CLT	F	6.2	0.5	-
V4-2	Gr. V4, 3-ply CLT	F	5.0	0.5	-
V4-3	Gr. V4, 3-ply CLT	F	5.5	0.6	-
V4-4	Gr. V4, 3-ply CLT	F	6.6	0.6	-
4NLT-1	2x4 NLT	F	6.2	-	-
4NLT-2	2x4 NLT	F	5.3	-	-
4NLT-3	2x4 NLT	F	4.7	-	-
6NLT-1	2x6 NLT	F	13.9	-	-
6NLT-2	2x6 NLT	F	14.0	-	-
6NLT-3	2x6 NLT	F	13.9	-	-

 Table 4-1. Limit State & Peak Pressure Test Results.

F: Flexural. Rupture due to flexural stress near mid-span localized near finger joints, sloped grain, and/or knots.
 V: Shear. Rupture due to rolling shear stress near support.

F/TB: Flexural with top board disengagement. Rupture due to flexural stress near mid-span localized near finger joints, sloped grain, and/or knots combined with top boards not supported by angle brackets popping upwards. V/TB: Shear with top board disengagement. Rupture due to rolling shear stress near support combined with top boards not

supported by angle brackets popping upwards.

N/A: Test apparatus failure prior to panel failing.

² Sum of peak forces recorded by load cells divided by 5,760 for "simple" end conditions and 5472 for "semi-rigid" end conditions.

³ Sum of (approximate) first plateau forces recorded by load cells divided by 5,760 for "simple" end conditions and 5472 for "semi-rigid" end conditions.

⁴ Sum of (approximate) second plateau forces recorded by load cells divided by 5,760 for "simple" end conditions and 5472 for "semi-rigid" end conditions.

Excluding the Grade V4 panels, which arrived to the lab much later, it is worth noting that the 5-ply CLT panel that failed in shear was the final CLT panel tested in the "simple" test setup configuration, and thus had the lowest moisture content (see Table 2-2). It was noted that as panels dried, significant inter-layer stresses developed leading to checking and some joint failure along the panel edges (see Figure 4-3). Thus, the different limit state observed for the final 5-ply test could be related to panel moisture content and the imperfections that resulted, but in the absence of further testing this theory is conjecture.



(a) Checking. (b) Bond Failure. Figure 4-3. Localized Deformation in CLT Panels.

The first test on a panel with connections (i.e., V1CA-1) resulted in one of the end pieces rotating, causing significant angle bracket deformation but minimal panel deformation (see Figure 4-4). Based on this test, modifications were made to the "semi-rigid" test setup configuration to constrain the end pieces. It should be noted that by constraining the end pieces, it is possible that panel arching between supports could occur, thus potentially augmenting the panel strength from a purely simply-supported condition.



Figure 4-4. Deformation of Simpson Bracket in V1-CA1.

The panels with the Simpson Strong-Tie (SST) angle brackets (i.e., V1CA-2 through V1CA-4) typically exhibited shear failures near one end of the panel (see Figure 4-5(a)). For the test in which four SST brackets were installed at each end (i.e., V1CA-2), the shear failure precipitated a flexural failure near panel mid-span. For the tests in which two and three SST brackets were installed at each end (i.e., V1CA-3 and V1CA-4), top boards not directly supported by angle brackets pulled away from those that were (see Figure 4-5(b)). In general, the SST brackets were capable of deforming significantly while still being able to support their respective loads (see Figure 4-5(c)). Additionally, both a small amount of wood crushing beneath the SST angle brackets and fastener pullout was observed (see Figure 4-5(d)).







(b) Top Board Disengagement.



(c) Bracket Deformation. (d) Wood Crushing & Fastener Pullout. Figure 4-5. Failure Modes Associated with Simpson Brackets.

By contrast, the panels with L4x4x1/4 angle brackets typically exhibited a flexural failure response near mid-span (see Figure 4-6(a)) similar to the predominant failure mode observed for panels tested in the "simple" test setup configuration. For the tests in which two brackets were installed at each end (i.e., V1CB-4), a few of the top boards not directly supported by angle brackets pulled away from those that were. As with the SST brackets, the L4x4x1/4 brackets yielded (see Figure 4-6(b)), but unlike the SST brackets, no fastener pullout or wood crushing was observed.



(a) Flexural Failure. (b) Bracket Deformation. Figure 4-6. Failure Modes Associated with L4x4x1/4 Brackets.

The NLT panels failed in flexure near panel mid-span. Typically, one stud would rupture first and then its neighbors would fail in a zippering fashion. This response led to highly unbalanced panels where one half was nearly intact and showed minimal deflection while the other half would be completely ruptured and have a mid-span deflection upwards of 10 inches. Figure 4-7 shows a typical example of this response.



Figure 4-7. Asymmetric Flexural Failure of NLT Panel.

Significant rotation of the boards relative to one another occurred due to the asymmetric deformation. Nail pullout and yielding was observed as well (see Figure 4-8). Prior to failure, panels were uniformly deflected. As some of the boards broke, the others rebounded as the pressure diminished and the water shifted to the failed portions of the panel.



Figure 4-8. Details of NLT Panel Failure.

4.2 RECORDED DATA

Typical failure pressures for 3-ply CLT and all NLT panels were between 5 and 8 psi, corresponding to a total load of between 28,000 and 46,000 pounds of applied load. The 5-ply CLT panels failed with a pressure of around 15 psi or about 86,000 pounds of applied load. The peak pressure resisted by each panel is recorded in Table 4-1.

Figure 4-9 includes plots of the data recorded for CLT panel test V1-4. These plots are representative of those obtained for 3-ply CLT panel flexural failures observed in the "simple" test setup configuration. Plots are included in Appendix B for the remainder of the tests. The text that follows describes how the plots were created and typical patterns observed.

- a) LC: This figure plots the force data from load cells 1 through 4 in time. Additionally, the sum of the load cell forces is plotted. In general, recordings from the individual load cells were relatively consistent, thus indicating the symmetric application of load by the rubber bladders.
- b) LC vs. PT 1: This figure plots the sum of the load cell force data in time divided by 5,760 in² (i.e., panel width multiplied by panel span) against the data recorded by the pressure transducer in the rubber bladder (i.e., PT 1). A 50-point running average filter was used to filter the pressure data.
- c) SP 1 SP 3: This figure plots the displacement data in time from string potentiometers (SPs) 1 through 3, or as shown in Figure 3-8, the SPs offset 12 inches to the north of panel mid-span.



Figure 4-9. Typical Data Recorded for "Simple" Test Setup Configuration (Test V1-4).

- d) SP 5 SP 7: This figure plots the displacement data in time from SPs 5 through 7, or as shown in Figure 3-8, the SPs at panel mid-span. As mentioned in Chapter 3, some SPs were lost when the panel ruptured suddenly. This gauge failure is indicated by an instantaneous drop in the displacement data. The SP 6 data shown in the plot is an example of this phenomenon.
- e) SP 9 SP 11: This figure plots the displacement data in time from SPs 9 through 11, or as shown in Figure 3-8, the SPs offset 12 inches to the south of panel mid-span. As with SP 6, SPs 10 and 11 were compromised in the process of panel rupture for this test.
- f) SP 4 & SP 8: This figure plots the displacement data in time from SPs 4 and 8, or as shown in Figure 3-8, the SPs located at the mid-span of the crossbar at each end of the panel. As observed from this plot, the deflection of the crossbar through the range of applied force is negligible.
- g) Average SP: This figure plots the average of the SP displacement data from each row for gauges that continuously recorded data for the duration of the test. The pressure values are based on the sum of the load cell force data (i.e., "LC Sum"), as this value is thought to better represent the actual force resisted by the panel.

As shown in Figure 4-9(g), 3-ply CLT panel response is essentially linear elastic prior to panel rupture. Upon panel rupture, there is a relatively sudden drop in panel strength to a residual panel strength. This residual panel strength remains relatively constant through a large deflection. Generally, the stroke of the SP was reached prior to the panel's strength dropping to zero.

For the 5-ply CLT panel, two residual strength plateaus are discernable in the recorded force-displacement data. The first plateau corresponds to the rupture of the outermost ply in tension and the second plateau corresponds to the rupture of the middle ply. This phenomenon is shown in Figure 4-10. It is interesting to note that the first residual strength plateau is relatively consistent in magnitude with that of the peak strength of the 3-ply CLT panel. This observation can be gleaned by comparing the data recorded in Table 4-1.



Figure 4-10. Ply Number Impact on Panel Response.

For the shear failure observed in test 5V1-5, the post-peak measurements are somewhat different. Figure 4-11 shows how instead of having two well defined plateaus, the shear failure shows one drop. However, it should be noted that test 5V1-5 was terminated at a much smaller deflection than tests 5V1-3 and 5V1-4.



Figure 4-11. Limit State Impact on Panel Response.

For several tests, particularly for those with connections, the LC Sum and PT 1 values diverge relatively significantly (see Figure 4-12). This divergence is attributed to: (1) the pretension forces placed on the threaded rods tying down the crossbar and (2) the rubber bladders not being in contact with the entire surface area of the panel.



Figure 4-12. Test Setup Configuration Impact on Load Measurement Data.

Finally, it is interesting to note the difference that the number of brackets might have had on the response of the panel. Qualitative observations are listed in the previous section, but the plots that quantify these differences are included in Figure 4-13.



Reviewing the NLT panel data resulted in similar observations made for the 3-ply CLT panels in the "simple" test setup configuration for the elastic range. However, following peak strength, due to the unbalanced failure pattern the gauges in the portion of the panel that did not fail rebounded (see SP 11 of Figure 4-14(a)). Also, those in the portion of the panel that failed broke in the violent rupture of the panel in many cases. Thus, the post peak response of the NLT panels as shown in Figure 4-14(b) is not representative of how the panel responded. It is interesting to note that a similar failure did not happen in the CLT panels, presumably due to the layer in the secondary direction that distributed the failure across the panel more evenly.



In addition to the observations made above, several tests suffered from abnormalities in the instrumentation or test setup that impaired data measurement:

- The shakedown test for the "simple" test setup configuration (i.e., V1-1) indicated issues with the load cell measurements (see Figure 4-15(a)).
- For test V1-3, LC 3 was defective (see Figure 4-15(b)).
- Leaking of the rubber bladders caused an early termination of test 5V1-1 (see Figure 4-15(c)).
- The SP data for test 5V1-3 recorded a sudden jump and then rebound in the elastic range (see Figure 4-15(d)). The cause of this jump/rebound is unknown and cannot be corroborated by video.



CHAPTER 5

CONCLUSIONS

The out-of-plane response of a selection of CLT and NLT panels was investigated using a test apparatus capable of applying a uniform quasi-static load. Grade, ply number, and connections were varied in the CLT panel testing and thickness was varied in the NLT panel testing. In this chapter, the applied load and panel displacement measurements are plotted together and compared with characteristic bending strength and stiffness values computed according to applicable standards. Additionally, observations made as a result of this testing are summarized.

5.1 DESIGN VALUE COMPARISON

The design bending strength (i.e., $F_bS_{eff,0}$) and effective bending stiffness (i.e., $EI_{eff,0}$) of CLT panels in the major strength direction is specified in Table A2 of ANSI/APA PRG 320-2012 [1] for Grades V1 and E1 CLT and in an APA supplement [2] for Grade V4 CLT. To obtain the characteristic values, $F_bS_{eff,0}$ was multiplied by 2.1 (i.e., consisting of a load duration factor, C_D , of 1.6 multiplied by a safety factor of 1.3 [3]). Figure 5-1 plots these characteristic bending strength and stiffness values for the 3-ply CLT panels against load-displacement plots created by using the average of the SP 5 through SP 7 (i.e., SP located at panel mid-span) displacement data and the sum of the load cell force data.



Figure 5-1. 3-Ply CLT Panel Load-Displacement Plots.

In general, the characteristic bending stiffness values are consistent with those obtained via testing. The bending strength values from testing are always greater, and in some cases, much greater than the characteristic bending strength values. For the Grade E1 CLT panels, which use MSR lumber in the major strength direction, the testing values are 5 to 40 percent greater than the characteristic values. However, for the Grades V1 and V4 CLT panels, which use visually graded lumber in the major strength direction, the testing values are approximately three times greater than the characteristic values.

Figure 5-2 creates a similar load-displacement plot for the 5-ply Grade V1 CLT panel tests. Again, the testing and characteristic bending stiffness values are consistent while the testing strength value is on the order of three times larger than the characteristic strength value.



Figure 5-2. 5-Ply Grade V1 CLT Panel Load-Displacement Plot.

The design bending strength and effective bending stiffness of NLT panels is computed using guidance for sawn lumber from ANSI/AF&PA NDS-2005 [4]. Actual, rather than nominal, dimensions are used to compute section properties. The plywood on the compression face of the panel is ignored for the purpose of computing the strength of the panel. Load duration (i.e., $C_D = 1.6$) and size (i.e., $C_F = 1.5$ for 2x4 NLT, $C_F = 1.3$ for 2x6 NLT) factors are applied to the bending strength value. Additionally, the design bending strength value is multiplied by 2.5 to transform the design value to the expected average value. This 2.5 factor is used in SBEDS [5], which is consistent with Breyer et al. (2007) [6]. Figure 5-3 plots these expected average bending strength and stiffness values against the tested values.



Figure 5-3. NLT Panel Load-Displacement Plots.

Initially, the expected average and tested bending stiffness values are consistent for the NLT panels. However, while the 2x4 NLT exhibits essentially linear response in the pre-peak region, the 2x6 NLT appears to exhibit a measure of nonlinearity. Whether this nonlinearity is related to the test setup or the panel itself is not known. Concerning strength, the expected average value is remarkably consistent for the 2x6 NLT. However, for the 2x4 NLT, the expected average value exceeds one of the tested values by approximately 25 percent.

Table 5-1 compares the average peak and residual strengths tabulated in Table 4-1 with those computed in this chapter using the applicable design standard. R_{test} values refer to testing values while R_{char} values refer to characteristic values. Characteristic residual strengths for the CLT panels were computed ignoring the ruptured major strength ply and minor strength ply directly below it. Thus, the "Residual Strength 1" value for a 5-ply CLT panel is assumed to be equivalent to that of a pristine 3-ply panel for the purpose of comparison. For the single ply condition, a flat use increase factor (i.e., 1.1 for Grade E1 CLT due to 2x4 boards and 1.15 for Grades V1 and V4 CLT due to 2x8 boards) was used in addition to a load duration factor of 1.6 and safety factor of 1.3 to augment the characteristic strength value.

		Peak Strength			Residual Strength 1			Residual Strength 2		
ID	Description	R _{test} (psi)	R _{char} (psi)	R _{test} / R _{char}	R _{test} (psi)	R _{char} (psi)	R _{test} / R _{char}	R _{test} (psi)	R _{char} (psi)	R _{test} / R _{char}
V1	Gr. V1 CLT	7.1	2.44	291%	1.6	0.38	421%	-	-	-
5V1	Gr. V1 CLT	15.2	5.61	271%	6.7	2.44	275%	2.7	0.38	711%
V1CA	Gr. V1 CLT	7.1	2.70	263%	4.1	0.42	976%	-	-	-
V1CB	Gr. V1 CLT	7.2	2.70	267%	2.9	0.42	690%	-	-	-
E1	Gr. E1 CLT	6.3	5.29	119%	1.4	0.79	177%	-	-	-
V4	Gr. V4 CLT	5.8	2.10	276%	0.55	0.33	167%	-	-	-
4NLT	2x4 NLT	5.4	5.95 ¹	91%	-	-	-	-	-	-
6NLT	2x6 NLT	13.9	12.74 ¹	109%	-	-	-	-	-	-

Table 5-1. Panel Strength Summary.

These values are expected average values rather than characteristic values. Characteristic values are meant to represent the 5% exclusion limit while expected average values are to be considered as mean values. Mean values were used for NLT to align with the current methodology used in SBEDS [5].

5.2 SUMMARY

5.2.1 CLT Panel without Connections

The CLT panel testing without connections yielded the following general observations:

- With one notable exception, all CLT panels without connections failed near panel midspan, presumably due to flexural stress. The location of panel rupture typically centered on knots, sloped grain, and finger joints.
- CLT panel response was essentially linear elastic prior to panel rupture. The tested stiffness of the panel was consistent with that specified in the applicable design standard. Upon panel rupture, there is a relatively sudden drop in panel strength to a residual panel strength plateau.

- The peak tested strength of Grade E1 panels with MSR lumber in the major strength direction was roughly 20 percent greater than the characteristic strength. On the other hand, the peak tested strength of Grade V1 and V4 panels with visually graded lumber in the major strength direction was roughly three times greater than the characteristic strength.
- The average residual panel strength plateau of the Grades E1 and V4 panels were roughly two times greater than the characteristic strength of a single ply member while the average residual panel strength plateau of the Grade V1 panel was at least four times greater than the characteristic strength of a single ply member.
- When CLT panels ruptured due to flexure, negligible shear slip between panel plies away from the location of panel rupture was observed.
- As panels dried, significant inter-layer stresses developed leading to checking and some joint failure along the panel edges. The shear failure observed for the final 5-ply test could be related to panel moisture content and the imperfections that resulted, but in the absence of further testing this theory is conjecture.
- No compression failure was observed in the panel, although for some panels a flexural failure of the lowest ply was observed towards the end of the test.

5.2.2 CLT Panel with Connections

Similarly, the CLT panel testing with connections yielded the following general observations:

- The peak strength of the CLT panel was independent of the number of angle brackets.
- In several tests, particularly for tests in which only two or three angle brackets were used at each end of the panel, top boards not directly supported by angle brackets pulled away from those that were.
- The panels with the Simpson Strong-Tie (SST) angle brackets typically exhibited shear failures near one end of the panel while those with the L4x4x1/4 angle brackets typically exhibited flexural failures near panel mid-span. One reason for this pattern could be that the SST brackets were connected by fasteners that penetrated only two of the three plies while the L4x4x1/4 bracket fasteners penetrated all three plies; however, this theory would need to be substantiated by additional testing or modeling.

5.2.3 NLT Panel without Connections

Finally, the NLT panel testing yielded the following general observations:

• The NLT panels failed in flexure near panel mid-span. Typically, one stud would rupture first and then its neighbors would fail in a zippering fashion. This response led to highly unbalanced panels where one half was nearly intact and showed minimal deflection while

the other half would be completely ruptured and have a mid-span deflection upwards of 10 inches.

• The average NLT bending stiffness and strength values obtained via testing are consistent with values computed using the NDS that ignore the impact of the plywood sheathing.

CHAPTER 6

REFERENCES

- [1] ANSI/APA PRG 320-2012, "Standard for Performance-Rated Cross-Laminated Timber", The Engineered Wood Association, 2012.
- [2] B.J. Yeh (personal communication, July 13, 2016).
- [3] B.J. Yeh (personal communication, April 13, 2016).
- [4] ANSI/AF&PA NDS-2005, "National Design Specification for Wood Construction with Commentary and Supplement: Design Values for Wood Construction", American Forest & Paper Association, 2005.
- [5] PDC-TR 06-01 Rev 2, "Methodology Manual for the Single-Degree-of-Freedom Blast Effects Design Spreadsheets (SBEDS)", US Army Corps of Engineers, December 2012. (*Export Controlled Distribution Statement C*)
- [6] Breyer et al., "Design of Wood Structures ASD/LRFD, 6th Edition", New York: McGraw Hill, 2007.

APPENDIX A

PHOTOGRAPHS OF EACH TEST


(a) Elevation view (looking west).



(b) Detail view (looking east). **Figure A-1. 3-Ply Grade V1 CLT – Test 1 (V1-1).**



(a) Elevation view (looking west).



(b) Detail view (looking east). (Note white plastic between adjacent boards.) Figure A-2. 3-Ply Grade V1 CLT – Test 2 (V1-2).



(a) Top view (looking west).



(b) Detail view (looking east). **Figure A-3. 3-Ply Grade V1 CLT – Test 3 (V1-3).**



(a) Elevation view (looking west).



(b) Initiation of failure (looking east). (Note failure at finger joint outside middle two feet.) **Figure A-4. 3-Ply Grade V1 CLT – Test 4 (V1-4).**



(a) Elevation view (looking west).



(b) Top view (looking east). (Note failure at finger joints near support, no finger joints located near panel mid-span.)
Figure A-5. 3-Ply Grade V1 CLT – Test 5 (V1-5).



(a) Elevation view (looking west). (Note bladder leakage at lower right.)



(b) Top view (looking east). Figure A-6. 5-Ply Grade V1 CLT – Test 1 (5V1-1).



(a) Elevation view (looking west). (Note this photo is taken just prior to bladder rupture.)



(b) Top view (looking east). Figure A-7. 5-Ply Grade V1 CLT – Test 2 (5V1-2).



(a) Top view (looking west).



(b) Detail view (looking east). Figure A-8. 5-Ply Grade V1 CLT – Test 3 (5V1-3).



(a) Elevation view (looking west).



Detail view (looking west). Figure A-9. 5-Ply Grade V1 CLT – Test 4 (5V1-4).



(a) Top view (looking west).



(b) Detail view (looking west). (Note slip between individual CLT plies.) Figure A-10. 5-Ply Grade V1 CLT – Test 5 (5V1-5).



(a) Top view (looking south).



(b) Detail view (looking west). **Figure A-11. 3-Ply Grade V1 CLT w/ SST Brackets at Each End – Test 1 (V1CA-1).**



(a) Initial shear failure (looking west).



(b) Subsequent flexural failure (looking west). Figure A-12. 3-Ply Grade V1 CLT w/ SST Brackets at Each End – Test 2 (V1CA-2).



(a) Elevation view (looking west).



(b) Top view. Figure A-13. 3-Ply Grade V1 CLT w/ SST Brackets at Each End – Test 3 (V1CA-3).



(a) Elevation view (looking west).



(b) Top view (looking west). Figure A-14. 3-Ply Grade V1 CLT w/ SST Brackets at Each End – Test 4 (V1CA-4).



(a) Top View (looking west).



(b) Detail view – bracket deformation (looking west). **Figure A-15. 3-Ply Grade V1 CLT w/ L4x4x1/4 Brackets at Each End – Test 1 (V1CB-1).**



(a) Elevation view (looking west).



(b) Detail view – bracket deformation (looking west). Figure A-16. 3-Ply Grade V1 CLT w/ L4x4x1/4 Brackets at Each End – Test 2 (V1CB-2).



(a) Top view (looking west).



(b) Detail view. Figure A-17. 3-Ply Grade V1 CLT w/ L4x4x1/4 Brackets at Each End – Test 3 (V1CB-3).



(a) Elevation view (looking west).



(b) Detail view (looking west). **Figure A-18. 3-Ply Grade E1 CLT – Test 1 (E1-1).**



(a) Elevation view (looking west).



(b) Detail view (looking west). Figure A-19. 3-Ply Grade E1 CLT – Test 2 (E1-2).



(a) Overall view (looking west).



(b) Detail view (looking east). **Figure A-20. 3-Ply Grade E1 CLT – Test 3 (E1-3).**



Figure A-21. 3-Ply Grade E1 CLT – Test 4 (E1-4).



Figure A-22. 3-Ply Grade V4 CLT – Test 1 (V4-1).



Figure A-23. 3-Ply Grade V4 CLT – Test 2 (V4-2).



(a) Initial failure.



(b) Subsequent failure. **Figure A-24. 3-Ply Grade V4 CLT – Test 3 (V4-3).**



(a) Elevation view (looking west).



(b) Shear slip at end. Figure A-25. 3-Ply Grade V4 CLT – Test 4 (V4-4).



Figure A-26. 2x4 NLT – Test 1 (4NLT-1).



Figure A-27. 2x4 NLT – Test 2 (4NLT-2).



Figure A-28. 2x4 NLT – Test 3 (4NLT-3).



(b) Top view. **Figure A-29. 2x6 NLT – Test 1 (6NLT-1).**



(a) Elevation view.



(b) Detail view. **Figure A-30. 2x6 NLT – Test 2 (6NLT-2).**



(a) Elevation view (looking east).



(b) Elevation view (looking west). Figure A-31. 2x6 NLT – Test 3 (6NLT-3).

APPENDIX B

RECORDED DATA FROM EACH TEST



(g) Average SP. Figure B-1. 3-Ply Grade V1 CLT – Test 1 (V1-1).



Figure B-2. 3-Ply Grade V1 CLT – Test 2 (V1-2).



Figure B-3. 3-Ply Grade V1 CLT – Test 3 (V1-3).



Figure B-4. 3-Ply Grade V1 CLT – Test 4 (V1-4).


Figure B-5. 3-Ply Grade V1 CLT – Test 5 (V1-5).



Figure B-6. 5-Ply Grade V1 CLT – Test 1 (5V1-1).

N/A	N/A
(a) LC.	<i>(b) LC vs. PT 1</i> .
N/A	N/A
(c) $SP \ 1 - SP \ 3$.	(d) $SP \ 5 - SP \ 7$.
N/A	N/A
(e) SP 9 – SP 11.	(f) SP 4 & SP 8.
	T (A





Figure B-8. 5-Ply Grade V1 CLT – Test 3 (5V1-3).



Figure B-9. 5-Ply Grade V1 CLT – Test 4 (5V1-4).



Figure B-10. 5-Ply Grade V1 CLT – Test 5 (5V1-5).

N/A	N/A
(a) LC.	<i>(b) LC vs. PT 1.</i>
N/A	N/A
(c) $SP \ 1 - SP \ 3$.	(d) $SP \ 5 - SP \ 7$.
N/A	N/A
(e) SP 9 – SP 11.	(f) SP 4 & SP 8.

N/A

(g) Average SP. Figure B-11. 3-Ply Grade V1 CLT w/ SST Brackets at Each End – Test 1 (V1CA-1).



Figure B-12. 3-Ply Grade V1 CLT w/ SST Brackets at Each End – Test 2 (V1CA-2).



Figure B-13. 3-Ply Grade V1 CLT w/ SST Brackets at Each End – Test 3 (V1CA-3).



Figure B-14. 3-Ply Grade V1 CLT w/ SST Brackets at Each End – Test 4 (V1CA-4).



Figure B-15. 3-Ply Grade V1 CLT w/ L4x4x1/4 Brackets at Each End – Test 1 (V1CB-1).



Figure B-16. 3-Ply Grade V1 CLT w/ L4x4x1/4 Brackets at Each End – Test 2 (V1CB-2).



Figure B-17. 3-Ply Grade V1 CLT w/ L4x4x1/4 Brackets at Each End – Test 3 (V1CB-3).



Figure B-18. 3-Ply Grade E1 CLT – Test 1 (E1-1).



Figure B-19. 3-Ply Grade E1 CLT – Test 2 (E1-2).



Figure B-20. 3-Ply Grade E1 CLT – Test 3 (E1-3).



Figure B-21. 3-Ply Grade E1 CLT – Test 4 (E1-4).



Figure B-22. 3-Ply Grade V4 CLT – Test 1 (V4-1).



Figure B-23. 3-Ply Grade V4 CLT – Test 2 (V4-2).



Figure B-24. 3-Ply Grade V4 CLT – Test 3 (V4-3).



Figure B-25. 3-Ply Grade V4 CLT – Test 4 (V4-4).



Figure B-26. 2x4 NLT – Test 1 (4NLT-1).



Figure B-27. 2x4 NLT – Test 2 (4NLT-2).



Figure B-28. 2x4 NLT – Test 3 (4NLT-3).







Figure B-31. 2x6 NLT – Test 3 (6NLT-3).