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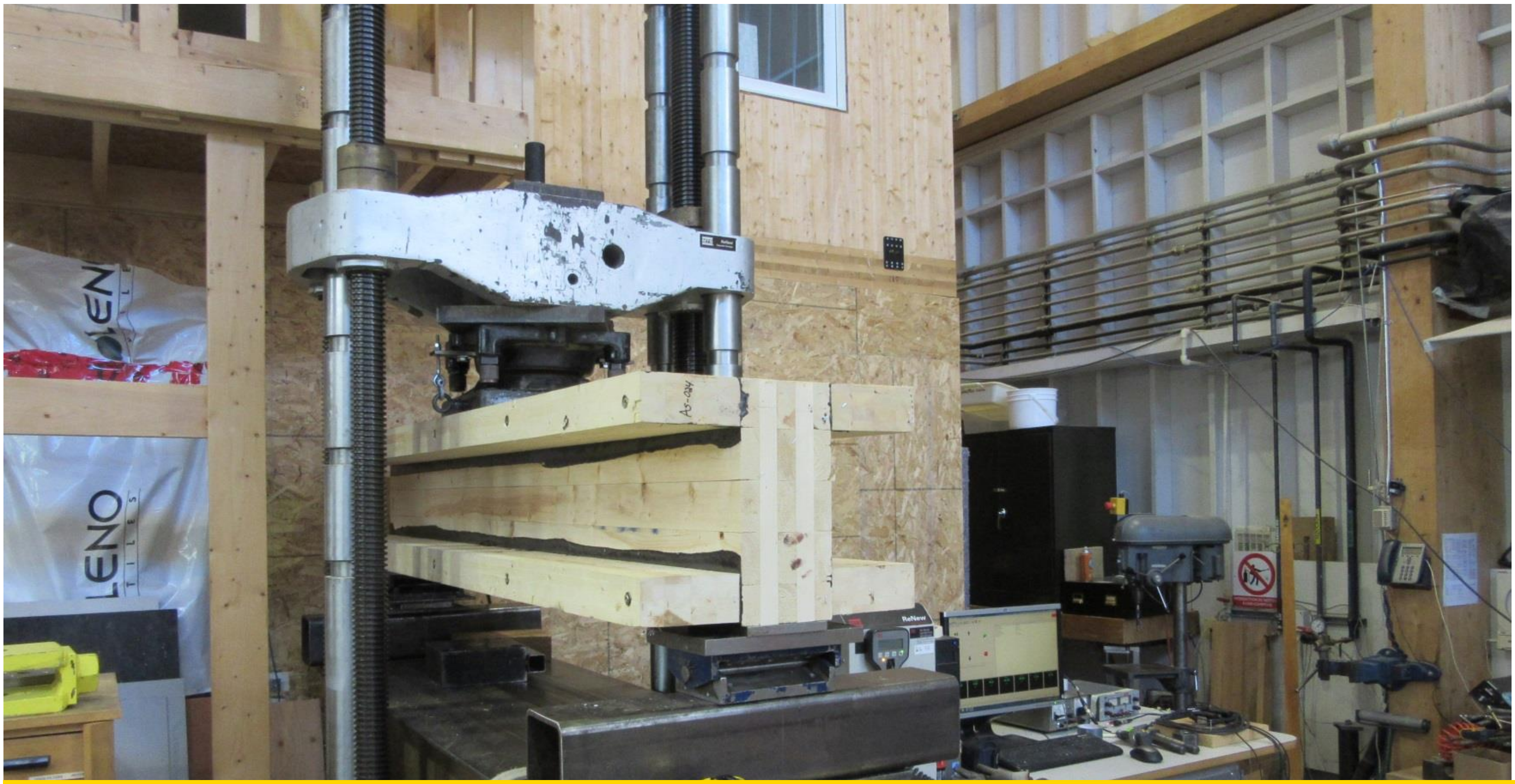

Shear Testing of Cross-Laminated Timber Beams

Date: March 22, 2016

By: Samuel Cuerrier Auclair, Jr. Eng., Researcher
Structural Performance, Advanced Building Systems Department

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PROJECT N^{O}: 301010956
Shear Testing of Cross-Laminated Timber Beams

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DATE: March 22, 2016

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1 INTRODUCTION

This testing program was carried out by the Advanced Building Systems (ABS) Department of FPInnovations in response to a request made by Mrs. Julie Frappier of Nordic Engineered Wood and Mr. Étienne Lalonde of Canadian Wood Council (CWC) for the evaluation of the shear stress resistance of one hundred fifty two (152) cross-laminated timber (CLT) beams. All specimens were manufactured by Nordic Engineered Wood and delivered to FPInnovations' testing facilities in Québec City.

2 OBJECTIVE

The main objective of this study was to evaluate the in-plane shear stress of CLT depending of its orientation and the number of plies. Specific Gravity and Moisture Content measurements were also determined for each specimen.

3 METHOD IDENTIFICATION

Testing procedures to determine the shear stress were performed in accordance with the principles of ASTM D2915-10 "Standard Practice for Sampling and Data-Analysis for Structural Wood and Wood-Based Products" and ASTM D5456-14 "Standard Specification for Evaluation of Structural Composite Lumber Products."

Specific Gravity (**SG**) and Moisture Content (**MC**) measurements were performed in accordance with ASTM D2395-07 and ASTM D 4442-07, respectively.

4 TECHNICAL TEAM

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Samuel Cuerrier Auclair, Jr. Eng.,	Scientist, Advanced Building Systems
Olivier Baës,	Principal Technologist, Advanced Building Systems
Anes Omeranovic,	Principal Technologist, Advanced Building Systems

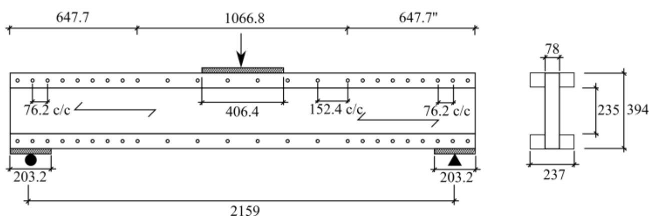
5 DESCRIPTION OF SAMPLES AND SAMPLING METHOD

5.1 Shear Tests

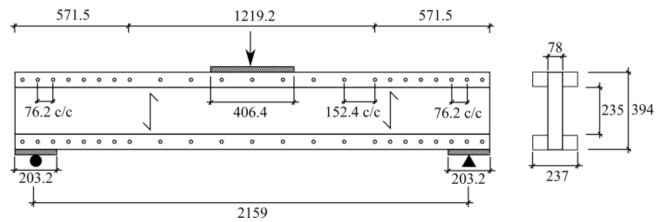
One hundred forty five (145) specimens were tested using eight (8) different configurations in a three-point loading test. The test set-ups for the eight (8) configurations with the CLT beam dimensions are provided in Figures 1 and 2. Additional screws were installed by FPInnovations except for the configuration shown on Figure 2(a) and (c) where these screws were installed by Nordic Engineered Wood. The CLT beams were reinforced with glulam of the same grade and species as CLT forming an I-shaped cross section in order to ensure shear failure throughout the testing schedule. The glulam beams were glued and screwed to the CLT. Steel loading blocks of 406.4 mm wide were used for the load transfer in order to minimize crushing in the top flange. A roller support was used in one extremity in order to allow the rotation and transversal displacement of the beam and a pinned support was used in the other extremity to allow rotation and prevent translation of the beam (rigid body motion). Figure 3 presents a specimen ready for testing at FPInnovations' testing facilities in Québec City.

A test machine with a 900-kN capacity was used in order to achieve the ultimate loads applying on the beam specimens. A computerized data acquisition system was used to record load measurements at an acquisition frequency of 5 Hz. No additional displacement measurement apparatus were employed since no precise displacements were pertinent for this study. The test speed of 2.5 mm/min was selected to ensure a time-to-failure around 10 to 15 minutes.

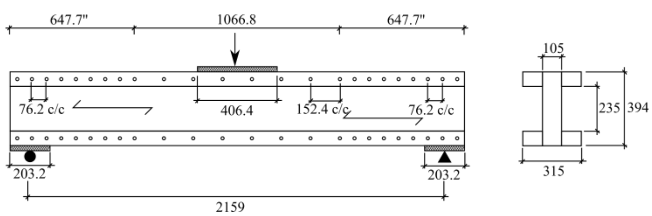
Photographs of the modes of failure were taken for each specimen.



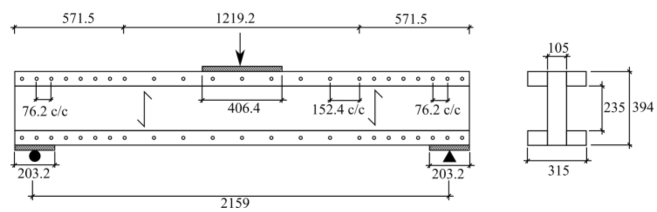
(a) 3-Ply-78-H



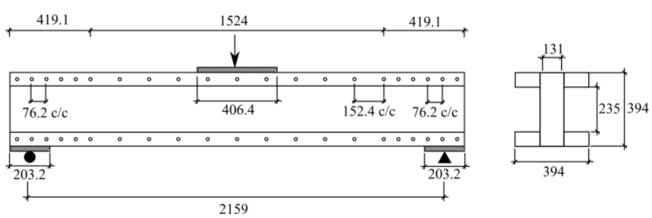
(b) 3-Ply-78-V



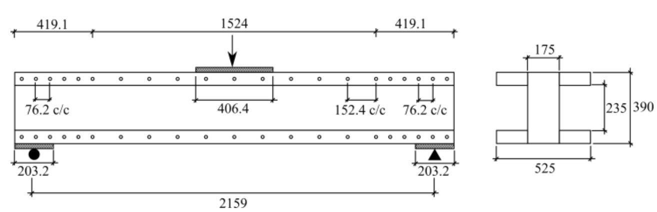
(c) 3-Ply-105-H1 to H10



(d) 3-Ply-105-V1 to V10

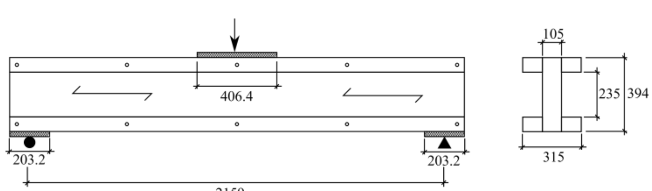


(e) 5-Ply-131-H and V

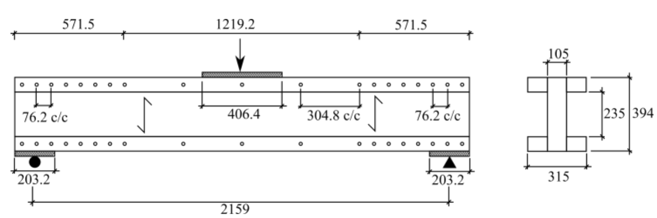


(f) 5-Ply-175-H2 to H11-a and V1 to V10

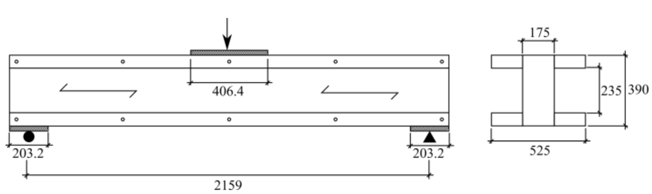
Figure 1 – Three point loading shear test set-up and reinforced CLT beam with glulam dimension for specimen received in April 2015



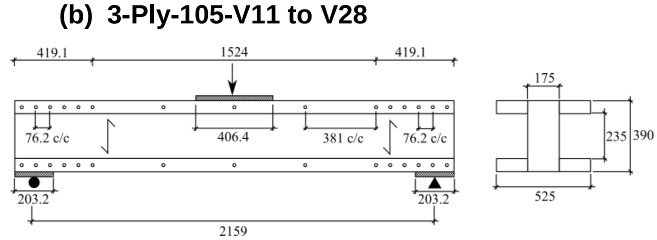
(a) 3-Ply-105-H11 to H28



(b) 3-Ply-105-V11 to V28



(c) 5-Ply-175-H11-b to H28



(d) 5-Ply-175-V11 to V28

Figure 2 – Three point loading shear test set-up and reinforced CLT beam with glulam dimension for specimen received in January 2016

Figure 3 – Reinforced CLT Beam with glulam at FPInnovations' Lab in Québec

5.2 Specific Gravity and Moisture Content

A slice of the beam cross section of approximately 25 mm wide was cut at approximately 150 mm inside of the extremes of each beam for the determination of Specific Gravity (**SG**) and Moisture Content (**MC**) as per ASTM D2395-07 and ASTM D 4442-07, respectively.

6 DATES OF RECEPTION OF SAMPLES

Eighty (80) specimens were received on April 13, 2015

Seventy two (72) specimens were received on January 26, 2016.

7 DATES OF TESTING

For the specimens received on April 2015, the testing started on June 29, 2015 and ended on September 11, 2015.

For the specimens received on January, 2016, the testing started on January 26, 2016 and ended on February 19, 2016.

8 EXPERIMENTAL METHOD

All measures were performed in general agreement with the specified standards and protocols. The precision levels were in accordance with the technical requirements.

9 RESULTS AND DISCUSSIONS

The specimens tested on April 2015 are identified by a yellow background in the tables below.

9.1 Shear Test Results

The results of the three point shear tests are provided in Tables 1 to 8 for all specimens tested. The apparent shear strength for each element has been calculated using the following equation as provided in ASTM D5456-14, Equation A3.1:

$$\tau_{Apparent} = \frac{3V}{2t}\frac{[bd^2 - (b - t\,)h^2]}{[bd^3 - (b - t)h^3]}$$

Where:

$\tau_{Apparent}$ = calculated shear strength, N/mm^2

V = ultimate shear force, N

b, d, t and h = geometrical parameters of the beams' cross section defined in Figure 4

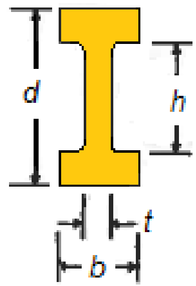


Figure 4 – Definitions of geometrical parameters for determination of apparent shear strength

Photographs of the mode of failure for each tested specimen are provided in the Appendix.

Tables 1 and 2 show the results for the 3-ply, 78 mm thick CLT, with the following dimensions expressed in mm:

$$b = 237 \text{ mm}, \quad t = 78 \text{ mm}, \quad d = 394 \text{ mm}, \quad h = 235 \text{ mm}$$

Table 1 – Shear test results for the 3-ply-78-H

#	Specimen ID 3-Ply-78	Peak Load (kN)	Shear Force (N)	$\tau_{Apparent}$ (MPa)	Failure Mode
1	H1	181.1	90566	3.92	Shear
2	H2	182.8	91403	3.96	Shear
3	H3	167.9	83947	3.64	Shear
4	H4	161.3	80659	3.49	Shear
5	H5	163.3	81663	3.54	Shear
6	H6	163.3	81658	3.54	Shear
7	H7	157.6	78814	3.41	Shear
8	H8	167.7	83872	3.63	Shear
9	H9	164.2	82102	3.56	Shear
10	H10	162.0	81021	3.51	Shear
	Minimum	**157.6**		**3.41**	
	Maximum	**182.8**		**3.96**	
	Mean	**167.1**		**3.62**	
	Std. Dev.	**8.4**		**0.18**	
	COV (%)	**5.0**		**5.0**	

Table 2 – Shear test results for the 3-ply-78-V

#	Specimen ID 3 Ply-78	Peak Load (kN)	Shear Force (N)	$\tau_{Apparent}$ (MPa)	Failure Mode
1	V1	217.3	108639	4.71	Shear
2	V2	204.3	102141	4.43	Shear
3	V3	215.1	107553	4.66	Shear
4	V4	220.5	110260	4.78	Shear
5	V5	221.4	110687	4.80	Shear
6	V6	184.5	92244	4.00	Shear
7	V7	194.6	97324	4.22	Shear
8	V8	212.7	106355	4.61	Shear
9	V9	203.3	101663	4.40	Shear
10	V10	207.8	103883	4.50	Shear
	Minimum	**184.5**		**4.00**	
	Maximum	**221.4**		**4.80**	
	Mean	**208.2**		**4.51**	
	Std. Dev.	**11.8**		**0.26**	
	COV (%)	**5.7**		**5.7**	

Tables 3 and 4 show the results for the 3-ply, 105 mm thick CLT, with the following dimensions expressed in mm: $b = 315\ \text{mm},\ t = 105\ \text{mm},\ d = 394\ \text{mm},\ h = 235\ \text{mm}$

Table 3 – Shear test results for the 3-ply-105-H

#	Specimen ID 3-Ply-105	Peak Load (kN)	Shear Force (N)	$\tau_{Apparent}$ (MPa)	Failure Mode
1	H1	173.3	86641	2.79	Shear
2	H2	144.5	72261	2.33	Shear
3	H3	165.8	82907	2.67	Shear
4	H4	168.6	84318	2.72	Shear
5	H5	134.1	67061	2.16	Shear
6	H6	163.3	81651	2.63	Shear
7	H7	150.7	75342	2.43	Shear
8	H8	132.3	66148	2.13	Shear
9	H9	152.4	76185	2.45	Shear
10	H10	166.3	83142	2.68	Shear
11	H11	204.5	102240	3.29	Shear
12	H12	182.2	91097	2.93	Shear
13	H13	188.7	94362	3.04	Shear
14	H14	192.9	96442	3.11	Shear
15	H15	187.9	93941	3.03	Shear
16	H16	197.3	98671	3.18	Shear
17	H17	190.9	95431	3.07	Shear
18	H18	189.1	94525	3.05	Shear
19	H19	192.4	96197	3.10	Shear
20	H20	189.7	94838	3.06	Shear
21	H21	191.6	95804	3.09	Shear
22	H22	189.2	94611	3.05	Shear
23	H23	193.8	96895	3.12	Shear
24	H24	184.8	92424	2.98	Shear
25	H25	198.7	99357	3.20	Shear
26	H26	199.4	99695	3.21	Shear
27	H27	179.1	89542	2.88	Shear
28	H28	190.2	95089	3.06	Shear
	Minimum	**132.3**		**2.13**	
	Maximum	**204.5**		**3.29**	
	Mean	**178.3**		**2.87**	
	Std. Dev.	**20.1**		**0.32**	
	COV (%)	**11.3**		**11.3**	

Table 4 – Shear test results for the 3-ply-105-V

#	Specimen ID 3-Ply-105	Peak Load (kN)	Shear Force, V (N)	$\tau_{Apparent}$ (MPa)	Failure Mode
1	V1	170.0	85017	2.74	Shear
2	V2	200.5	100252	3.23	Shear
3	V3	181.1	90548	2.92	Shear
4	V4	194.6	97276	3.13	Shear
5	V5	192.6	96320	3.10	Shear
6	V6	193.0	96495	3.11	Shear
7	V7	196.6	98303	3.17	Shear
8	V8	201.3	100663	3.24	Shear
9	V9	175.2	87592	2.82	Shear
10	V10	193.2	96600	3.11	Shear
11	V11	226.2	113091	3.64	Shear/Glued failure
12	V12	220.6	110303	3.55	Shear
13	V13	211.3	105666	3.40	Shear
14	V14	225.7	112848	3.64	Shear
15	V15	232.2	116076	3.74	Shear
16	V16	228.3	114160	3.68	Shear
17	V17	226.1	113032	3.64	Shear
18	V18	210.2	105121	3.39	Shear
19	V19	219.0	109515	3.53	Shear
20	V20	214.6	107283	3.46	Shear
21	V21	219.4	109718	3.53	Shear
22	V22	225.6	112784	3.63	Shear
23	V23	234.9	117474	3.78	Shear
24	V24	217.6	108804	3.51	Shear/Glued failure
25	V25	232.7	116339	3.75	Shear
26	V26	229.2	114617	3.69	Shear
27	V27	217.8	108876	3.51	Shear
28	V28	243.1	121531	3.92	Shear
	Minimum	**170.0**		**2.74**	
	Maximum	**243.1**		**3.92**	
	Mean	**211.9**		**3.41**	
	Std. Dev.	**19.1**		**0.31**	
	COV (%)	**9.0%**		**9.0%**	

Tables 5 and 6 show the results for the 5-ply, 131 mm thick CLT, with the following dimensions expressed in mm:

$$b = 394 \text{ mm}, \qquad t = 131 \text{ mm}, \qquad d = 394 \text{ mm}, \qquad h = 235 \text{ mm}$$

Table 5 – Shear test results for the 5-ply-131-H

#	Specimen ID 5-Ply-131	Peak Load (kN)	Shear Force (N)	$\tau_{Apparent}$ (MPa)	Failure Mode
1	H1	299.2	149603	3.86	Shear
2	H2	300.6	150280	3.88	Shear
3	H3	314.2	157109	4.06	Shear
4	H4	309.9	154935	4.00	Shear
5	H5	322.5	161261	4.16	Shear
6	H6	324.0	162000	4.18	Shear/bending
7	H7	343.3	171668	4.43	Shear
8	H8	293.2	146612	3.79	Shear
9	H9	322.1	161056	4.16	Shear
10	H10	336.9	168425	4.35	Shear
	Minimum	**293.2**		**3.79**	
	Maximum	**343.3**		**4.43**	
	Mean	**316.6**		**4.09**	
	Std. Dev.	**16.3**		**0.21**	
	COV (%)	**5.2**		**5.3**	

Table 6 – Shear test results for the 5-ply-131-V

#	Specimen ID 5-Ply-131	Peak Load (kN)	Shear Force (N)	$\tau_{Apparent}$ (MPa)	Failure Mode
1	V1	303.1	1515675	3.91	Bending
2	V2	336.2	168095	4.34	Bending
3	V3	309.0	154524	3.99	Bending
	Mean	**316.1**		**4.08**	

Since the three first specimens tested with the 5-ply-131-V configuration failed in bending, which indicates that the bending capacity is lower than the shear capacity, it was decided not to test the other specimens in this configuration.

Tables 7 and 8 show the results for the 5-ply, 175 mm thick CLT, with the following dimensions expressed in mm: $b = 525 \text{ mm}, \ t = 175 \text{ mm}, \ d = 390 \text{ mm}, \ h = 235 \text{ mm}$

Table 7 – Shear test results for the 5-ply-175-H

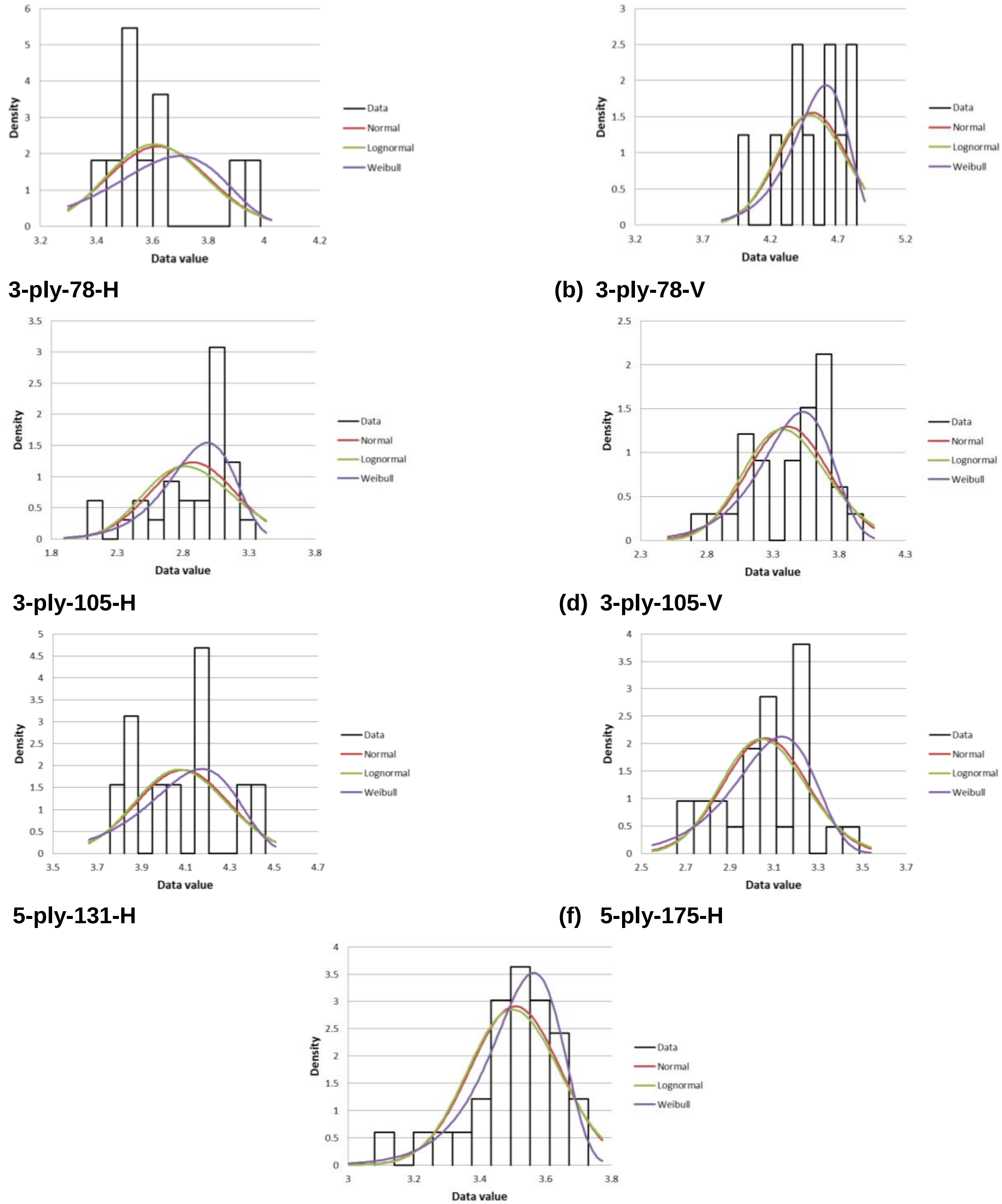
#	Specimen ID 5-Ply-175	Peak Load (kN)	Shear Force (N)	$\tau_{Apparent}$ (MPa)	Failure Mode
1	H2	291.1	145554	2.84	Shear
2	H3	285.3	142644	2.78	Shear
3	H4	278.2	139115	2.71	Shear/Bending
4	H5	306.1	153066	2.99	Shear
5	H6	293.5	146731	2.86	Shear
6	H7	301.3	150637	2.94	Shear
7	H8	287.5	143757	2.80	Shear
8	H9	332.6	166305	3.24	Shear
9	H10	317.0	158500	3.09	Shear
10	H11-a	276.9	138455	2.70	Shear
11	H11-b	304.4	152207	2.97	Shear
12	H12	354.0	177014	3.45	Shear/Bending
13	H13	316.7	158352	3.09	Shear
14	H14	327.9	163966	3.20	Shear
15	H15	343.3	171655	3.35	Shear
16	H16	312.6	156311	3.05	Shear
17	H17	329.6	164791	3.21	Shear
18	H18	332.9	166429	3.25	Shear
19	H19	328.7	164350	3.21	Shear
20	H20	313.8	156894	3.06	Shear
21	H21	320.8	160394	3.13	Shear
22	H22	329.4	164720	3.21	Shear
23	H23	316.1	158045	3.08	Shear
24	H24	330.0	165001	3.22	Shear/Bending
25	H25	309.1	154529	3.01	Shear
26	H26	330.7	165364	3.23	Shear
27	H27	306.9	153456	2.99	Shear
28	H28	315.2	157623	3.07	Shear
	Minimum	**276.9**		**2.70**	
	Maximum	**354.0**		**3.45**	
	Mean	**314.0**		**3.06**	
	Std. Dev.	**19.4**		**0.19**	
	COV (%)	**6.2%**		**6.2%**	

Table 8 – Shear test results for the 5-ply-175-V

#	Specimen ID 5-Ply-175	Peak Load (kN)	Shear Force (N)	$\tau_{Apparent}$ (MPa)	Failure Mode
1	V1	379.1	189554	3.70	Shear
2	V2	354.2	177107	3.45	Shear
3	V3	339.5	169727	3.31	Shear
4	V4	359.7	179856	3.51	Shear
5	V5	378.2	189085	3.69	Shear
6	V6	354.5	177245	3.46	Shear
7	V7	354.7	177364	3.46	Shear
8	V8	370.6	185312	3.61	Shear/Bending
9	V9	332.7	166348	3.24	Shear/Bending
10	V10	318.8	159381	3.11	Shear
11	V11	350.7	175346	3.42	Shear/Bending
12	V12	348.2	174122	3.40	Shear/Bending
13	V13	363.4	181716	3.54	Shear
14	V14	355.5	177734	3.47	Shear
15	V15	342.8	171389	3.34	Shear
16	V16	367.3	183626	3.58	Shear
17	V17	361.5	180750	3.53	Shear
18	V18	367.0	183506	3.58	Shear/Bending
19	V19	370.8	185378	3.62	Shear
20	V20	373.1	186561	3.64	Shear
21	V21	361.5	180738	3.52	Shear
22	V22	368.1	184072	3.59	Shear
23	V23	361.8	180912	3.53	Shear
24	V24	373.8	186897	3.64	Shear
25	V25	376.5	188269	3.67	Shear
26	V26	358.0	179009	3.49	Shear/Bending
27	V27	367.7	183863	3.59	Shear/Bending
28	V28	360.9	180472	3.52	Shear/Bending
	Minimum	**318.8**		**3.11**	
	Maximum	**379.1**		**3.70**	
	Mean	**359.7**		**3.51**	
	Std. Dev.	**14.0**		**0.14**	
	COV (%)	**3.90%**		**3.9%**	

9.2 Statistical analysis

The characteristic value of each configuration was estimated following the principles of ASTM D2915-10 with a confidence of 75% that at least 95% of the population's capacity is greater than the calculated value. Since not every configuration had 28 specimens, a parametric analysis was performed on each configuration considering the normal, lognormal and Weibull distribution. Figure 5 shows the statistic distribution and the parametric analysis for each configuration, except for configuration 5-ply-131-V.



(a) 3-ply-78-H

(b) 3-ply-78-V

(c) 3-ply-105-H

(d) 3-ply-105-V

(e) 5-ply-131-H

(f) 5-ply-175-H

(g) 5-ply-175-V

Figure 5 – Statistic distribution for each configuration with parametric analysis

Table 9 – Estimated characteristic value of in-plane shear for each configuration

Configuration	Number of Tested Specimens	Average Value (MPa)	Min. Value (MPa)	Characteristic Value (5% Tolerance Limit – 75% Confidence) (MPa)	Method
3-ply-78-H	10	3.62	3.41	3.07	Parametric: Weibull
3-ply-78-V	10	4.51	4.00	3.97	Parametric: Weibull
3-ply-105-H	28	2.87	2.13	2.13	Non parametric
3-ply-105-V	28	3.41	2.74	2.79	Parametric: Weibull
5-ply-131-H	10	4.09	3.79	3.53	Parametric: Weibull
5-ply-175-H	28	3.06	2.70	2.62	Parametric: Weibull
5-ply-175-V	28	3.51	3.11	3.23	Parametric: Weibull

NOTE: The estimated characteristic value is only valid if the tested specimens were selected randomly in order to have the better possible representation of the CLT production. Adjustment factors need to be included to get the specified in-plane shear strength (for ASD and LSD).

9.3 Specific Gravity and Moisture Content

Values for the Specific Gravity (**SG**) and Moisture Content (**%MC**) for every specimen are provided in Tables 10 to 17 as per ASTM D2395-07 and ASTM D 4442-07, respectively. The given Specific Gravity is for the over-dried wood.

Table 10 – SG and MC for the 3-ply-78-H

#	Specimen ID 3-Ply-78	Specific Gravity (Kg/m^3)	Humidity (%)
1	H1	505.8	15.4
2	H2	523.6	18.3
3	H3	514.8	17.0
4	H4	516.7	13.6
5	H5	529.6	13.7
6	H6	515.9	14.4
7	H7	546.0	12.6
8	H8	522.1	14.6
9	H9	501.2	12.6
10	H10	536.1	13.7
	Minimum	**501.2**	**12.6**
	Maximum	**546.0**	**18.3**
	Mean	**521.2**	**14.6**
	Std. Dev.	**13.49**	**1.86**
	COV (%)	**2.6**	**12.7**

Table 11 – SG and MC for the 3-ply-78-V

#	Specimen ID 3-Ply-78	Specific Gravity (Kg/m^3)	Humidity (%)
1	V1	506.2	15.3
2	V2	484.6	12.6
3	V3	516.8	14.5
4	V4	472.8	20.8
5	V5	521.9	12.4
6	V6	520.1	14.0
7	V7	517.1	12.9
8	V8	481.4	13.7
9	V9	491.5	14.2
10	V10	514.9	13.5
	Minimum	**472.8**	**12.4**
	Maximum	**521.9**	**20.8**
	Mean	**502.7**	**14.4**
	Std. Dev.	**18.37**	**2.41**
	COV (%)	**3.7**	**16.8**

Table 12 – SG and MC for the 3-ply-105-H

#	Specimen ID 3-Ply-105	Specific Gravity (Kg/m^3)	Humidity (%)
1	H1	525.9	11.7
2	H2	546.1	11.6
3	H3	519.2	11.8
4	H4	482.5	11.9
5	H5	477.6	11.6
6	H6	498.8	11.8
7	H7	489.6	11.7
8	H8	488.7	11.5
9	H9	479.8	11.6
10	H10	501.0	11.6
11	H11	520.5	13.0
12	H12	489.9	12.8
13	H13	477.7	13.0
14	H14	480.4	12.3
15	H15	510.1	13.1
16	H16	483.4	13.0
17	H17	468.6	12.7
18	H18	464.1	12.6
19	H19	470.1	12.9
20	H20	515.9	13.9
21	H21	503.5	13.1
22	H22	497.2	12.8
23	H23	486.6	13.1
24	H24	486.3	12.9
25	H25	483.7	13.2
26	H26	512.3	12.9
27	H27	526.0	12.4
28	H28	516.2	12.2
	Minimum	**464.1**	**11.5**
	Maximum	**546.1**	**13.9**
	Mean	**496.5**	**12.5**
	Std. Dev.	**20.38**	**0.67**
	COV (%)	**4.1**	**5.4**

Table 13 – SG and MC for the 3-ply-105-V

#	Specimen ID 3-Ply-105	Specific Gravity (Kg/m^3)	Humidity (%)
1	V1	472.1	11.9
2	V2	490.9	11.9
3	V3	491.1	11.9
4	V4	489.5	11.6
5	V5	507.2	12.0
6	V6	514.9	11.7
7	V7	509.9	12.2
8	V8	517.5	12.5
9	V9	510.9	12.4
10	V10	483.8	12.1
11	V11	492.2	11.9
12	V12	494.8	12.7
13	V13	480.4	13.2
14	V14	479.8	12.7
15	V15	515.4	12.6
16	V16	507.7	12.1
17	V17	504.6	12.7
18	V18	516.6	13.7
19	V19	515.9	13.1
20	V20	485.7	13.4
21	V21	489.7	13.1
22	V22	514.6	13.8
23	V23	515.2	13.4
24	V24	494.1	13.2
25	V25	490.7	13.2
26	V26	495.1	13.2
27	V27	492.6	13.7
28	V28	507.9	13.2
	Minimum	**472.1**	**11.6**
	Maximum	**517.5**	**13.8**
	Mean	**499.3**	**12.7**
	Std. Dev.	**13.38**	**0.66**
	COV (%)	**2.7**	**5.2**

Table 14 – SG and MC for the 5-ply-131-H

#	Specimen ID 5-Ply-131	Specific Gravity (Kg/m^3)	Humidity (%)
1	H1	531.0	11.6
2	H2	507.6	11.6
3	H3	517.0	12.1
4	H4	522.1	11.5
5	H5	509.5	11.6
6	H6	503.0	11.8
7	H7	509.6	11.8
8	H8	515.4	12.1
9	H9	482.5	11.9
10	H10	552.6	12.2
	Minimum	**482.5**	**11.5**
	Maximum	**552.6**	**12.2**
	Mean	**515.0**	**11.8**
	Std. Dev.	**18.36**	**0.25**
	COV (%)	**3.6**	**2.1**

Table 15 – SG and MC for the 5-ply-131-V

#	Specimen ID 5-Ply-131	Specific Gravity (Kg/m^3)	Humidity (%)
1	V1	534.2	11.4
2	V2	516.4	11.3
3	V3	490.0	11.5
	Mean	**513.6**	**11.4**

Table 16 – SG and MC for the 5-ply-175-H

#	Specimen ID 5-Ply-175	Specific Gravity (Kg/m^3)	Humidity (%)
1	H2	478.9	12.6
2	H3	464.9	12.2
3	H4	473.5	12.4
4	H5	551.3	12.3
5	H6	418.6	11.9
6	H7	525.8	12.3
7	H8	521.4	12.4
8	H9	488.3	13.2
9	H10	494.0	12.3
10	H11-a	483.6	12.0
11	H11-b	511.7	13.0
12	H12	499.3	12.9
13	H13	505.2	13.4
14	H14	487.0	13.2
15	H15	505.6	12.9
16	H16	479.5	12.0
17	H17	503.1	12.5
18	H18	486.1	12.3
19	H19	487.7	12.7
20	H20	494.3	13.5
21	H21	508.7	12.4
22	H22	498.4	13.0
23	H23	451.6	12.3
24	H24	479.8	13.1
25	H25	506.5	13.8
26	H26	516.2	13.2
27	H27	494.4	12.6
28	H28	481.0	13.1
	Minimum	**418.6**	**11.9**
	Maximum	**551.3**	**13.8**
	Mean	**492.7**	**12.7**
	Std. Dev.	**24.66**	**0.50**
	COV (%)	**5.0**	**3.9**

Table 17 – SG and MC for the 5-ply-175-V

#	Specimen ID 5-Ply-175	Specific Gravity (Kg/m^3)	Humidity (%)
1	V1	470.4	12.9
2	V2	508.0	13.2
3	V3	471.8	13.5
4	V4	460.6	13.3
5	V5	478.2	13.1
6	V6	518.7	12.5
7	V7	496.9	12.5
8	V8	511.7	12.4
9	V9	507.7	12.6
10	V10	506.8	13.0
11	V11	482.3	12.6
12	V12	485.3	13.2
13	V13	512.9	13.0
14	V14	490.2	13.1
15	V15	502.8	13.1
16	V16	505.4	12.8
17	V17	475.0	13.3
18	V18	477.9	12.8
19	V19	488.2	12.5
20	V20	494.4	12.8
21	V21	484.7	13.3
22	V22	506.1	12.6
23	V23	497.4	12.2
24	V24	485.8	13.5
25	V25	504.7	12.1
26	V26	461.9	13.4
27	V27	502.4	12.6
28	V28	463.0	12.8
	Minimum	**460.6**	**12.1**
	Maximum	**518.7**	**13.5**
	Mean	**491.1**	**12.9**
	Std. Dev.	**16.77**	**0.38**
	COV (%)	**3.4**	**3.0**

10 CONCLUSION

A testing program consisting of one hundred forty five (145) reinforced CLT beams with glulam was performed with eight (8) different configurations in a three-point loading test at FPInnovations' testing facilities in Québec City with the objective of evaluating the characteristic value (5% Tolerance Limit with 75% Confidence) of in-plane CLT in accordance with the principles of ASTM D2915-10 "Standard Practice for Sampling and Data-Analysis for Structural Wood and Wood-Based Products" and ASTM D5456-14 "Standard Specification for Evaluation of Structural Composite Lumber Products."

Initially, one hundred fifty two (152) CLT beams were supposed to be tested. However, the first three tests of the 5-ply, 131 mm thick CLT configuration with a vertical orientation of the external ply (5-ply-131-V) have shown no sign of shear failure, so it was decided to stop the testing program for this configuration. The same value as that of the 5-ply, 175 mm thick CLT with a vertical orientation of the external ply (5-ply-175-V) could be used for this configuration as a conservative design value.

In agreement with the analyses and observations made during the course of this study, the following conclusions and recommendations can be determined:

- When comparing CLT beams with the same thickness and number of plies, the CLT beams with a vertical orientation of the external ply show a higher shear capacity than the CLT beams with a horizontal orientation of the external ply;
- The highest estimated characteristic value of in-plane shear is of **3.97 MPa** for the 3-ply, 78 mm thick CLT, with a vertical orientation of the external ply (3-ply-78-V) and the smallest characteristic value is of **2.13 MPa** for the 3-ply, 105 mm thick CLT, with a horizontal orientation of the external ply (3-ply-105-H);

11 REFERENCES

ASTM 2014. Annual Book of ASTM Standards, Volume 04.10 Wood. ASTM, Philadelphia, Pa.

APPENDIX I

Photographs of the Modes of Failure

3Ply-78-H

H1

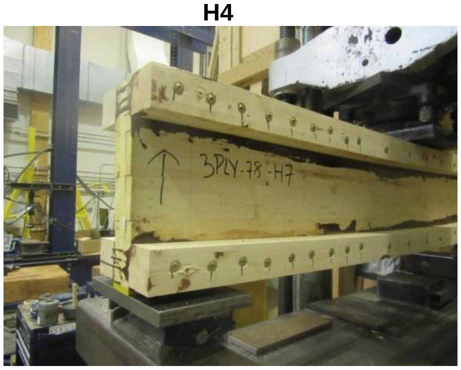
H2

H3

H4

H5

H6



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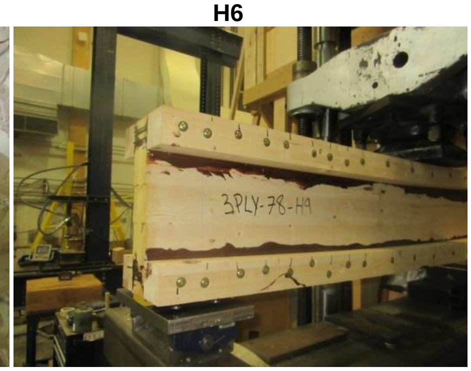
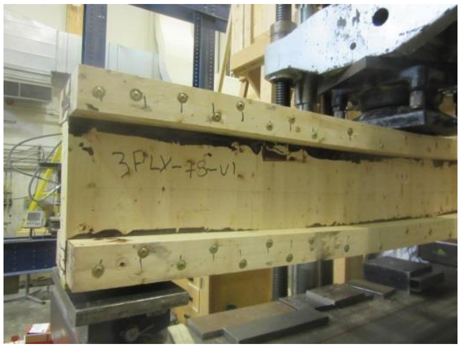


H9

H10

3-Ply-78-V



V1

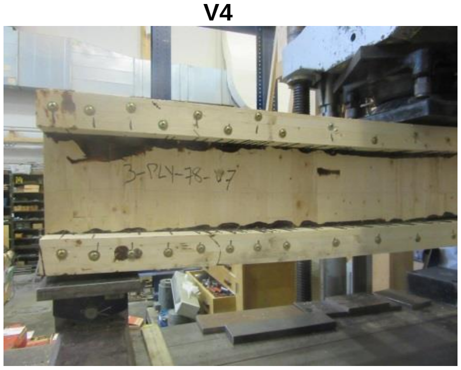
V2

V3

V4

V5

V6



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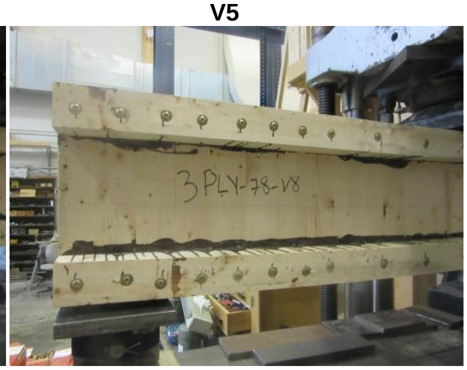

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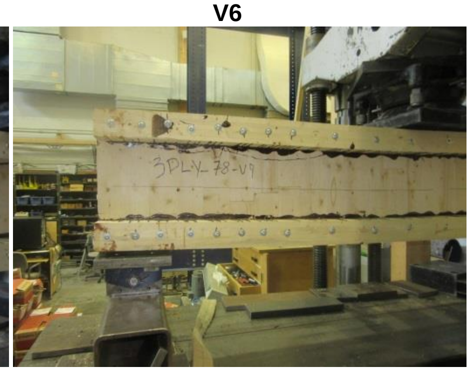

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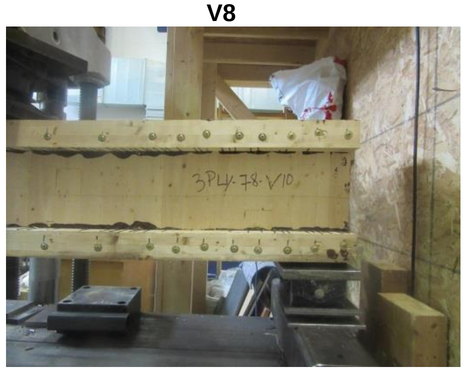


V10

3-Ply-105-H

H1

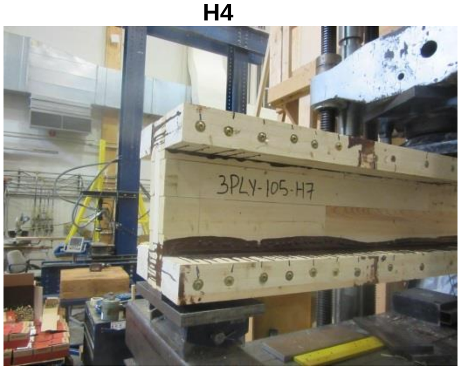
H2

H3

H4

H5

H6



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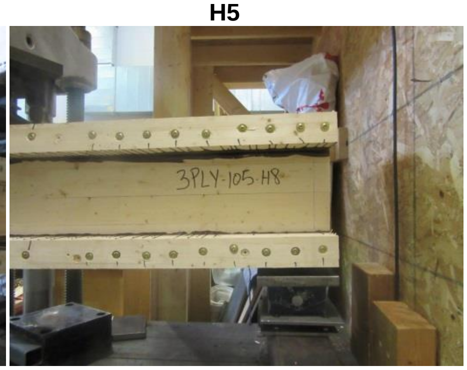

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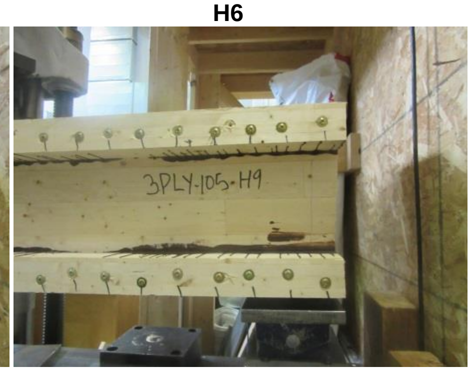

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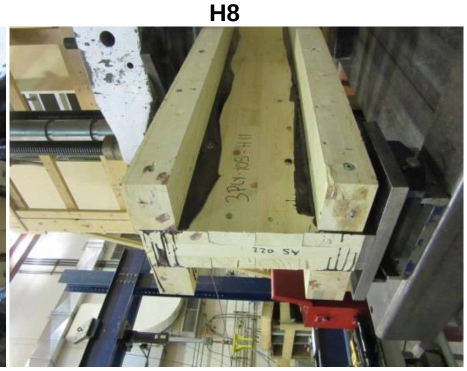
H10



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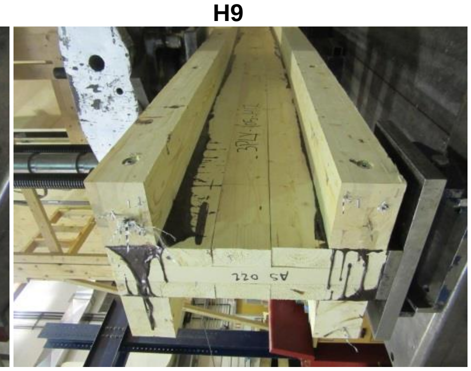

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3-Ply-105-H (continued)

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H14

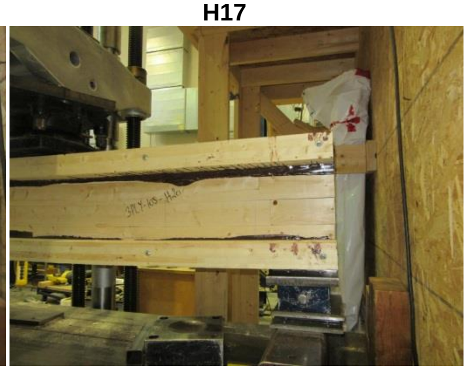
H15

H16

H17

H18

H19



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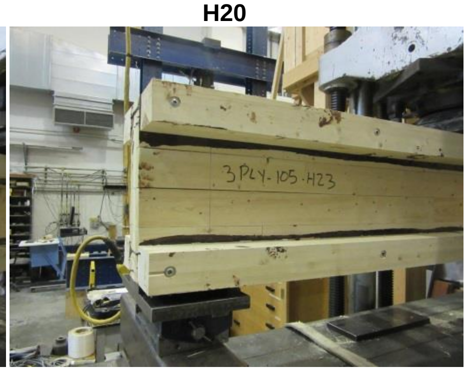


H23

H24

3-Ply-105-H (continued)

H25

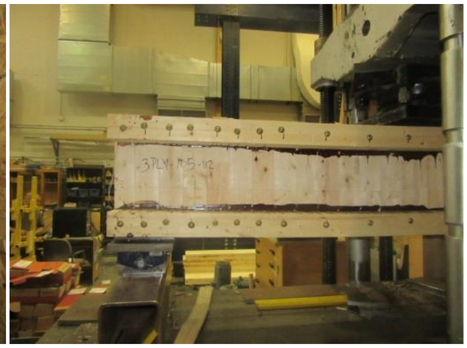
H26

H27

H28

3-Ply-105-V


V1

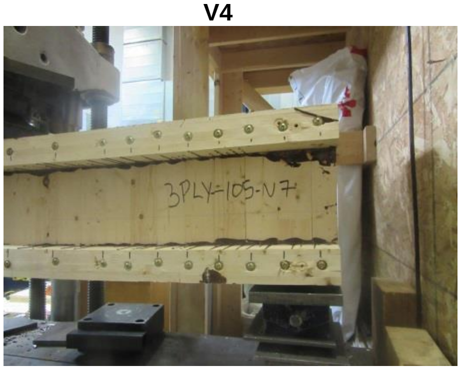

V2

V3

V4

V5

V6



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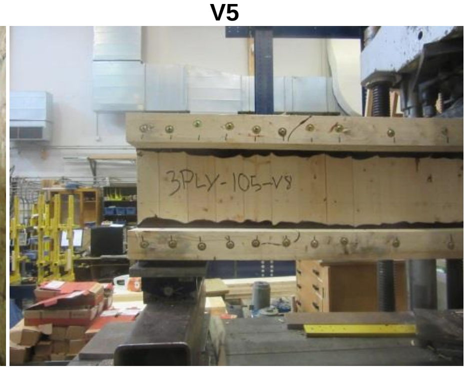

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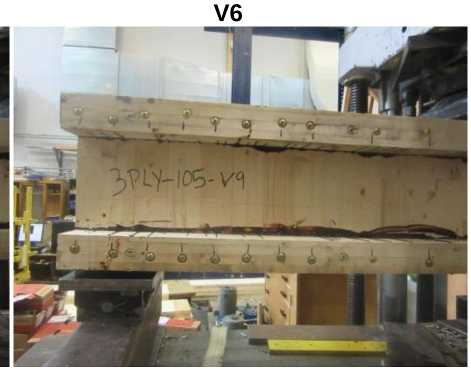

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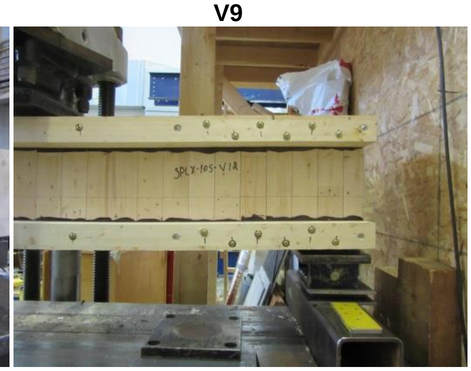
V10

V11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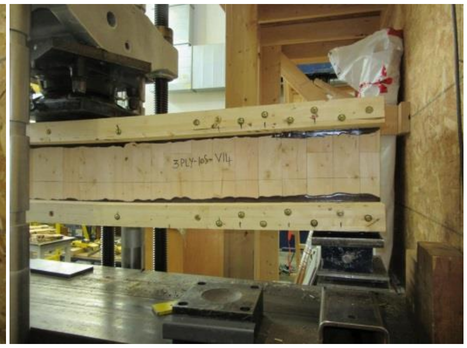
3-Ply-105-V (continued)

V13



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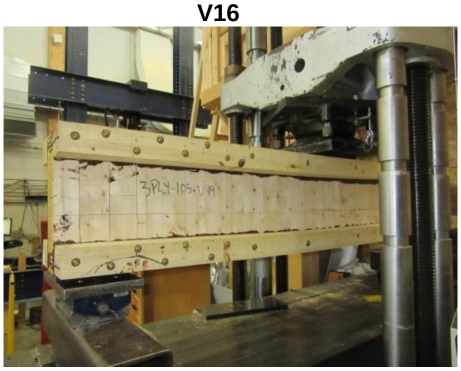
V15

V16

V17

V18



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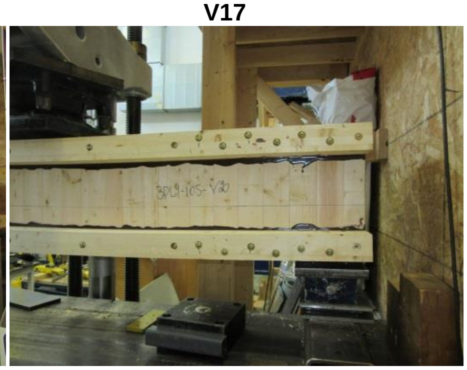

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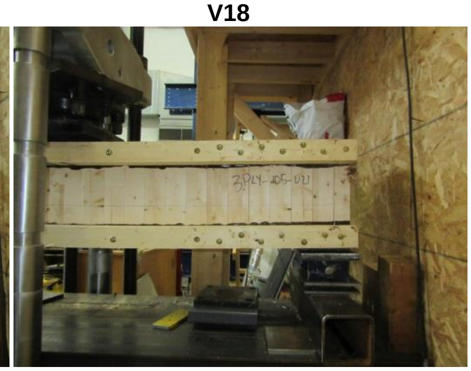

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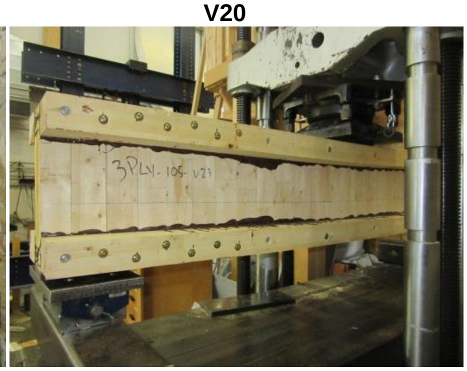

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V24

3-Ply-105-V (continued)

V25

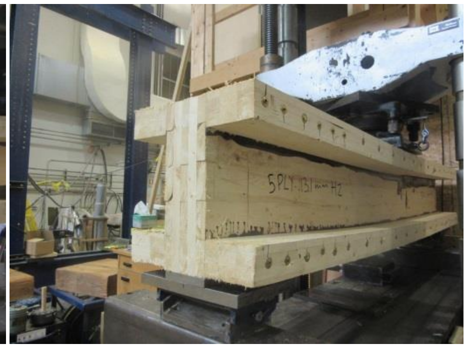
V26

V27

V28

5-Ply-131-H

H1



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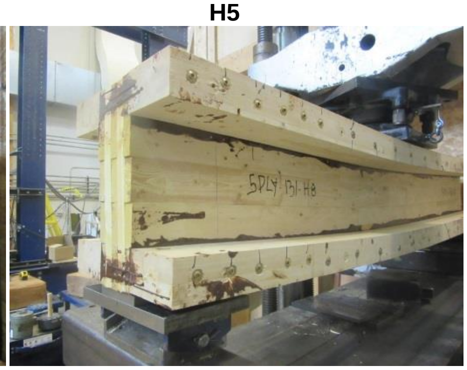
H5

H6

H7



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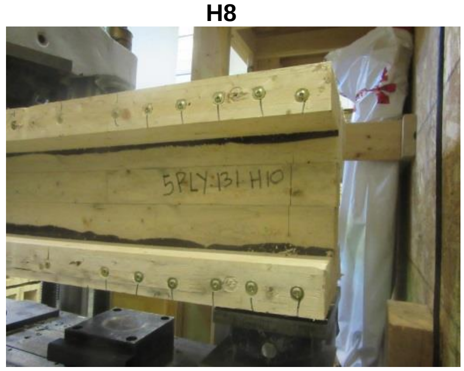


H10

5-Ply-131-V

V1

V2

V3

5-Ply-175-H

H2

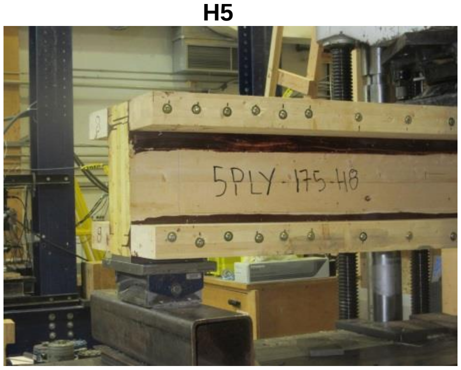
H3

H4

H5

H6

H7



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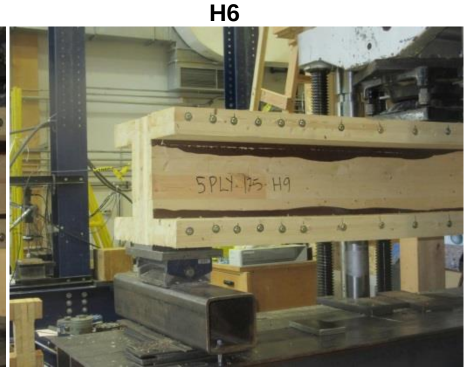

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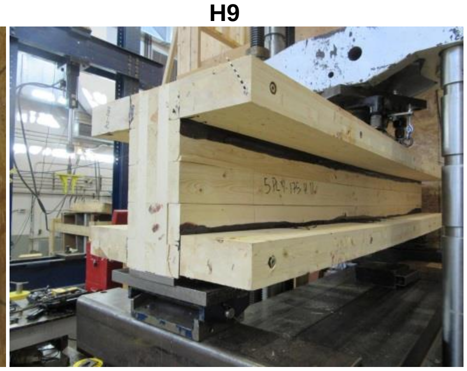
H10

H11-a



H11-b

H12

5-Ply-175-H (continued)

H13

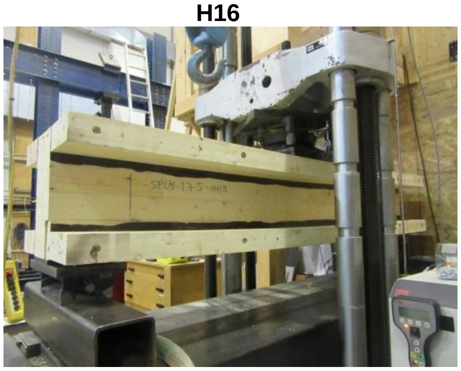
H14

H15

H16

H17

H18



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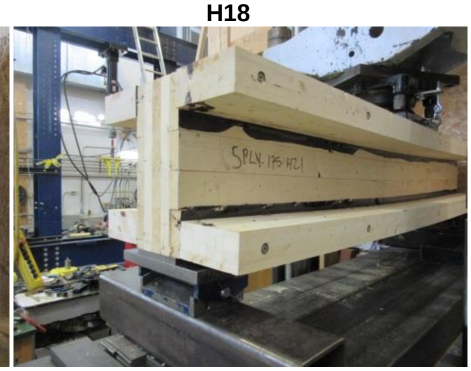

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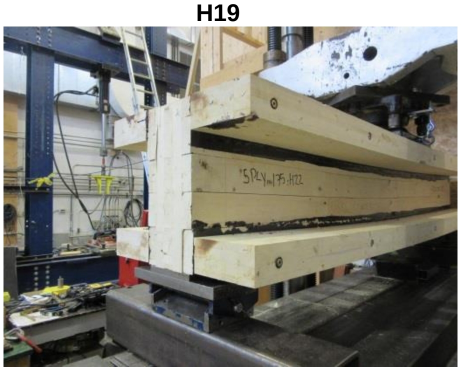

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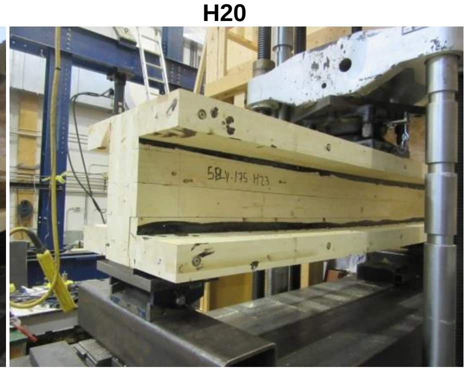


H23

H24

5-Ply-175-H (continued)

H25

H26

H27

H28

5-Ply-175-V

V1

V2

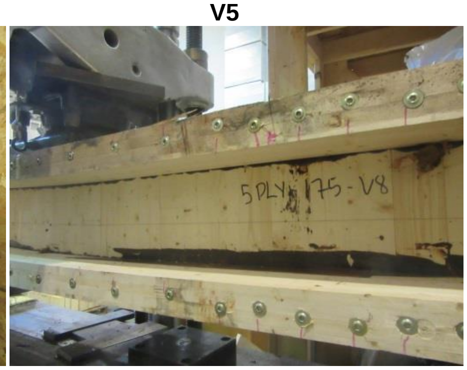
V3

V4

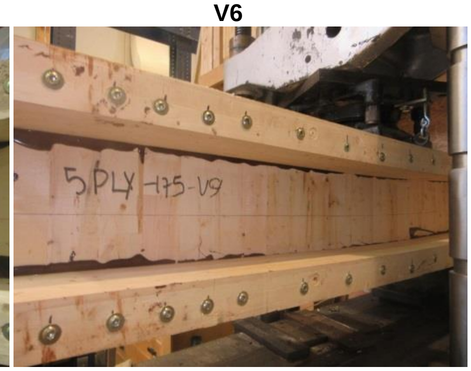
V5

V6

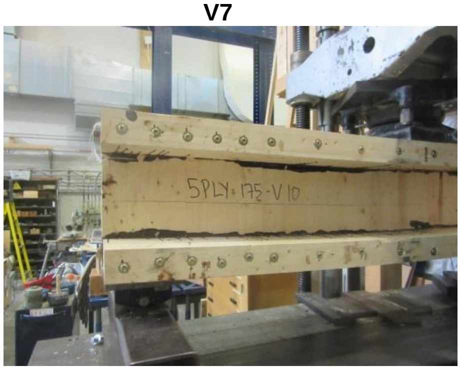
V7



V8



V9



V10

V11

V12

5-Ply-175-V (continued)

V13

V14

V15

V16

V17

V18

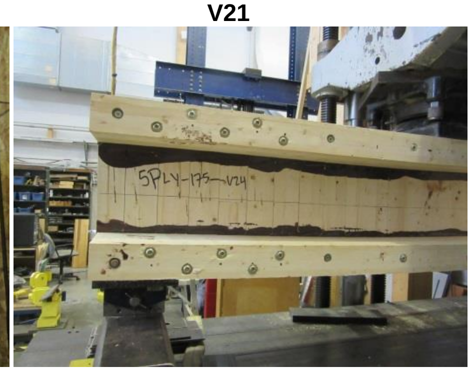
V19

V20

V21

V22

V23



V24

5-Ply-175-V (continued)

V25

V26

V27

V28

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