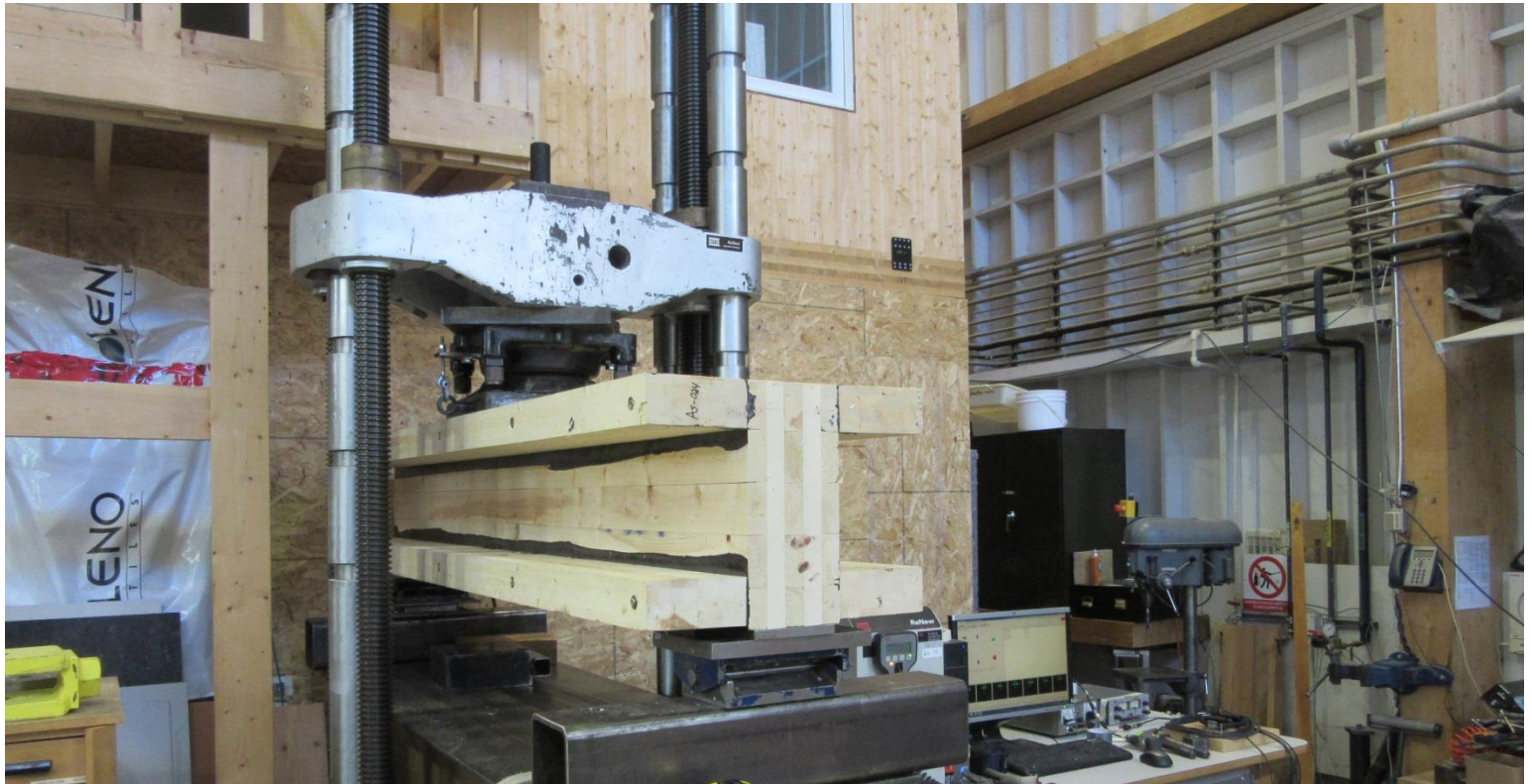




# Shear Testing of Cross-Laminated Timber Beams

**Date:** March 22, 2016

**By:** Samuel Cuerrier Auclair, Jr. Eng., Researcher  
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Shear Testing of Cross-Laminated Timber Beams

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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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## 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.

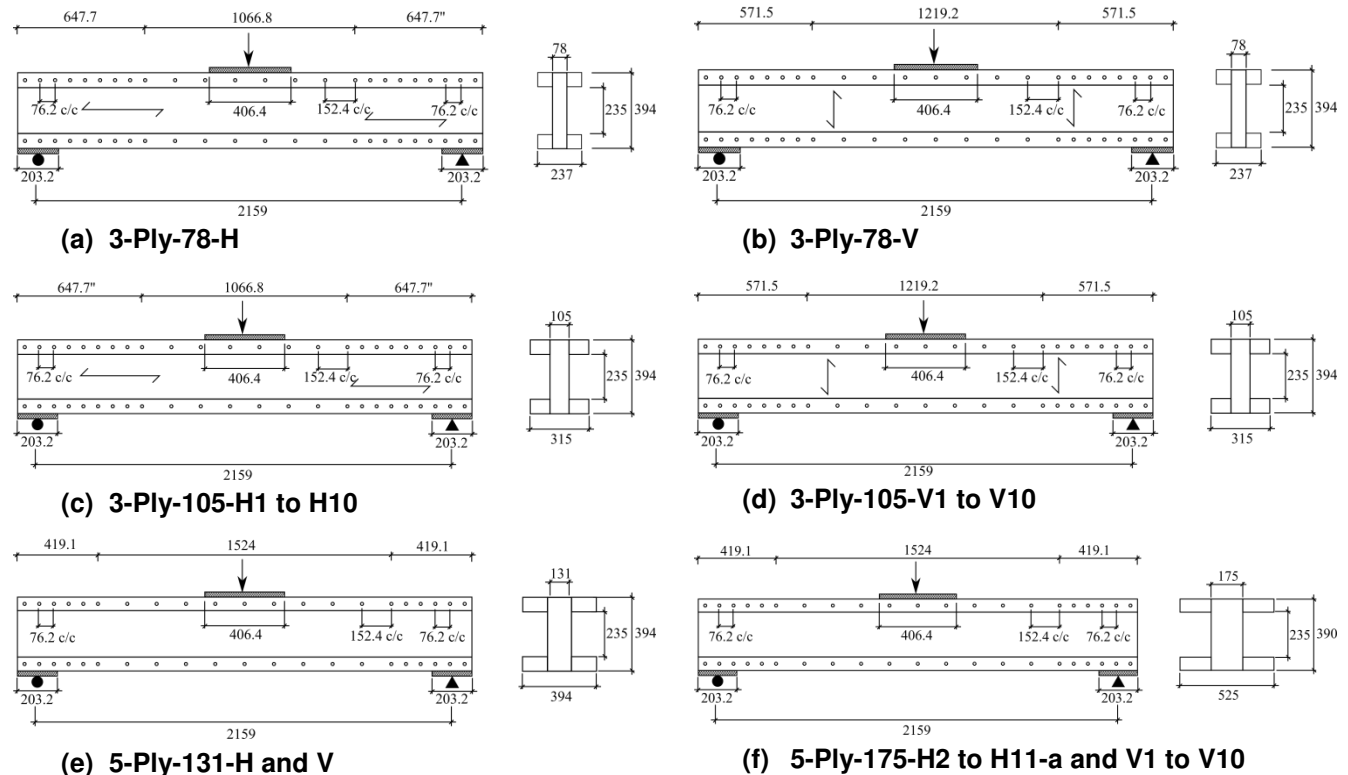


Figure 1 – Three point loading shear test set-up and reinforced CLT beam with glulam dimension for specimen received in April 2015

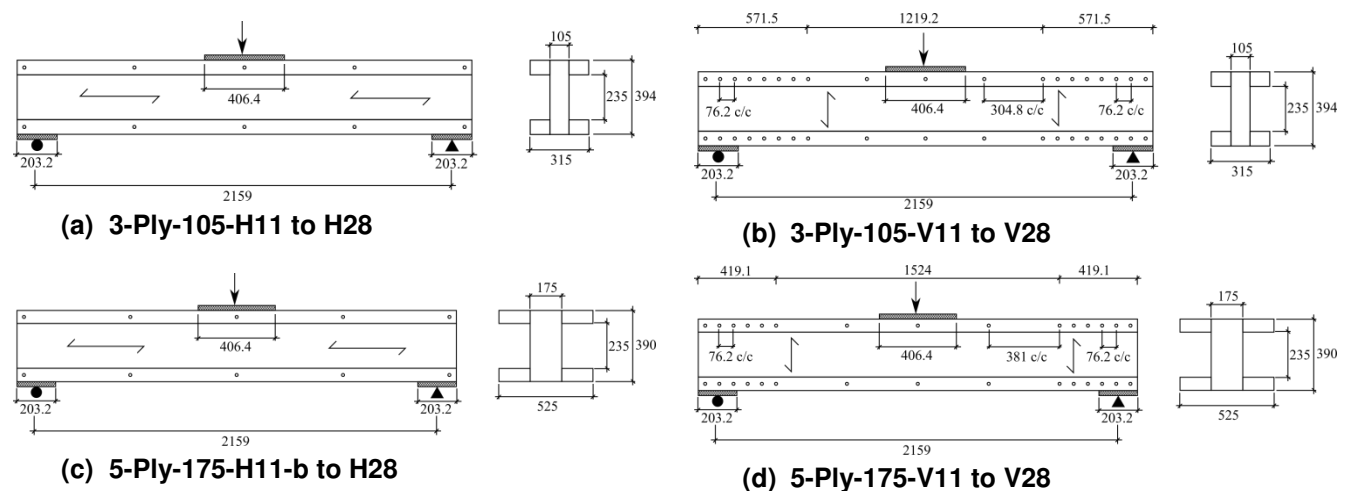


Figure 2 – Three point loading shear test set-up and reinforced CLT beam with glulam dimension for specimen received in January 2016



Figure 3 – Reinforced CLT Beam with glulam at FPIInnovations' 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:

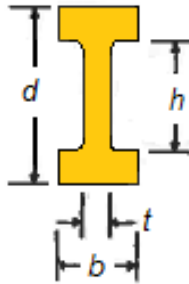
$$\tau_{Apparent} = \frac{3V [bd^2 - (b - t)h^2]}{2t [bd^3 - (b - t)h^3]}$$

Where:

$\tau_{Apparent}$  = calculated shear strength, N/mm<sup>2</sup>

$V$  = 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<br>3-Ply-78 | Peak Load<br>(kN) | Shear Force<br>(N) | $\tau_{Apparent}$<br>(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        |
|    | <b>Minimum</b>          | <b>157.6</b>      |                    | <b>3.41</b>                |              |
|    | <b>Maximum</b>          | <b>182.8</b>      |                    | <b>3.96</b>                |              |
|    | <b>Mean</b>             | <b>167.1</b>      |                    | <b>3.62</b>                |              |
|    | <b>Std. Dev.</b>        | <b>8.4</b>        |                    | <b>0.18</b>                |              |
|    | <b>COV (%)</b>          | <b>5.0</b>        |                    | <b>5.0</b>                 |              |

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

| #  | Specimen ID<br>3 Ply-78 | Peak Load<br>(kN) | Shear Force<br>(N) | $\tau_{Apparent}$<br>(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        |
|    | <b>Minimum</b>          | <b>184.5</b>      |                    | <b>4.00</b>                |              |
|    | <b>Maximum</b>          | <b>221.4</b>      |                    | <b>4.80</b>                |              |
|    | <b>Mean</b>             | <b>208.2</b>      |                    | <b>4.51</b>                |              |
|    | <b>Std. Dev.</b>        | <b>11.8</b>       |                    | <b>0.26</b>                |              |
|    | <b>COV (%)</b>          | <b>5.7</b>        |                    | <b>5.7</b>                 |              |

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

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

| #  | Specimen ID<br>3-Ply-105 | Peak Load<br>(kN) | Shear Force<br>(N) | $\tau_{\text{Apparent}}$<br>(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        |
|    | <b>Minimum</b>           | <b>132.3</b>      |                    | <b>2.13</b>                       |              |
|    | <b>Maximum</b>           | <b>204.5</b>      |                    | <b>3.29</b>                       |              |
|    | <b>Mean</b>              | <b>178.3</b>      |                    | <b>2.87</b>                       |              |
|    | <b>Std. Dev.</b>         | <b>20.1</b>       |                    | <b>0.32</b>                       |              |
|    | <b>COV (%)</b>           | <b>11.3</b>       |                    | <b>11.3</b>                       |              |

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

| #  | Specimen ID<br>3-Ply-105 | Peak Load<br>(kN) | Shear Force, V<br>(N) | $\tau_{\text{Apparent}}$<br>(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               |
|    | <b>Minimum</b>           | <b>170.0</b>      |                       | <b>2.74</b>                       |                     |
|    | <b>Maximum</b>           | <b>243.1</b>      |                       | <b>3.92</b>                       |                     |
|    | <b>Mean</b>              | <b>211.9</b>      |                       | <b>3.41</b>                       |                     |
|    | <b>Std. Dev.</b>         | <b>19.1</b>       |                       | <b>0.31</b>                       |                     |
|    | <b>COV (%)</b>           | <b>9.0%</b>       |                       | <b>9.0%</b>                       |                     |

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

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

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

| #  | Specimen ID<br>5-Ply-131 | Peak Load<br>(kN) | Shear Force<br>(N) | $\tau_{\text{Apparent}}$<br>(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         |
|    | <b>Minimum</b>           | <b>293.2</b>      |                    | <b>3.79</b>                       |               |
|    | <b>Maximum</b>           | <b>343.3</b>      |                    | <b>4.43</b>                       |               |
|    | <b>Mean</b>              | <b>316.6</b>      |                    | <b>4.09</b>                       |               |
|    | <b>Std. Dev.</b>         | <b>16.3</b>       |                    | <b>0.21</b>                       |               |
|    | <b>COV (%)</b>           | <b>5.2</b>        |                    | <b>5.3</b>                        |               |

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

| # | Specimen ID<br>5-Ply-131 | Peak Load<br>(kN) | Shear Force<br>(N) | $\tau_{\text{Apparent}}$<br>(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      |
|   | <b>Mean</b>              | <b>316.1</b>      |                    | <b>4.08</b>                       |              |

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:  $b = 525$  mm,  $t = 175$  mm,  $d = 390$  mm,  $h = 235$  mm

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

| #  | Specimen ID<br>5-Ply-175 | Peak Load<br>(kN) | Shear Force<br>(N) | $\tau_{Apparent}$<br>(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         |
|    | <b>Minimum</b>           | <b>276.9</b>      |                    | <b>2.70</b>                |               |
|    | <b>Maximum</b>           | <b>354.0</b>      |                    | <b>3.45</b>                |               |
|    | <b>Mean</b>              | <b>314.0</b>      |                    | <b>3.06</b>                |               |
|    | <b>Std. Dev.</b>         | <b>19.4</b>       |                    | <b>0.19</b>                |               |
|    | <b>COV (%)</b>           | <b>6.2%</b>       |                    | <b>6.2%</b>                |               |

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

| #  | Specimen ID<br>5-Ply-175 | Peak Load<br>(kN) | Shear Force<br>(N) | $\tau_{\text{Apparent}}$<br>(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 |
|    | <b>Minimum</b>           | <b>318.8</b>      |                    | <b>3.11</b>                       |               |
|    | <b>Maximum</b>           | <b>379.1</b>      |                    | <b>3.70</b>                       |               |
|    | <b>Mean</b>              | <b>359.7</b>      |                    | <b>3.51</b>                       |               |
|    | <b>Std. Dev.</b>         | <b>14.0</b>       |                    | <b>0.14</b>                       |               |
|    | <b>COV (%)</b>           | <b>3.90%</b>      |                    | <b>3.9%</b>                       |               |

## 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.

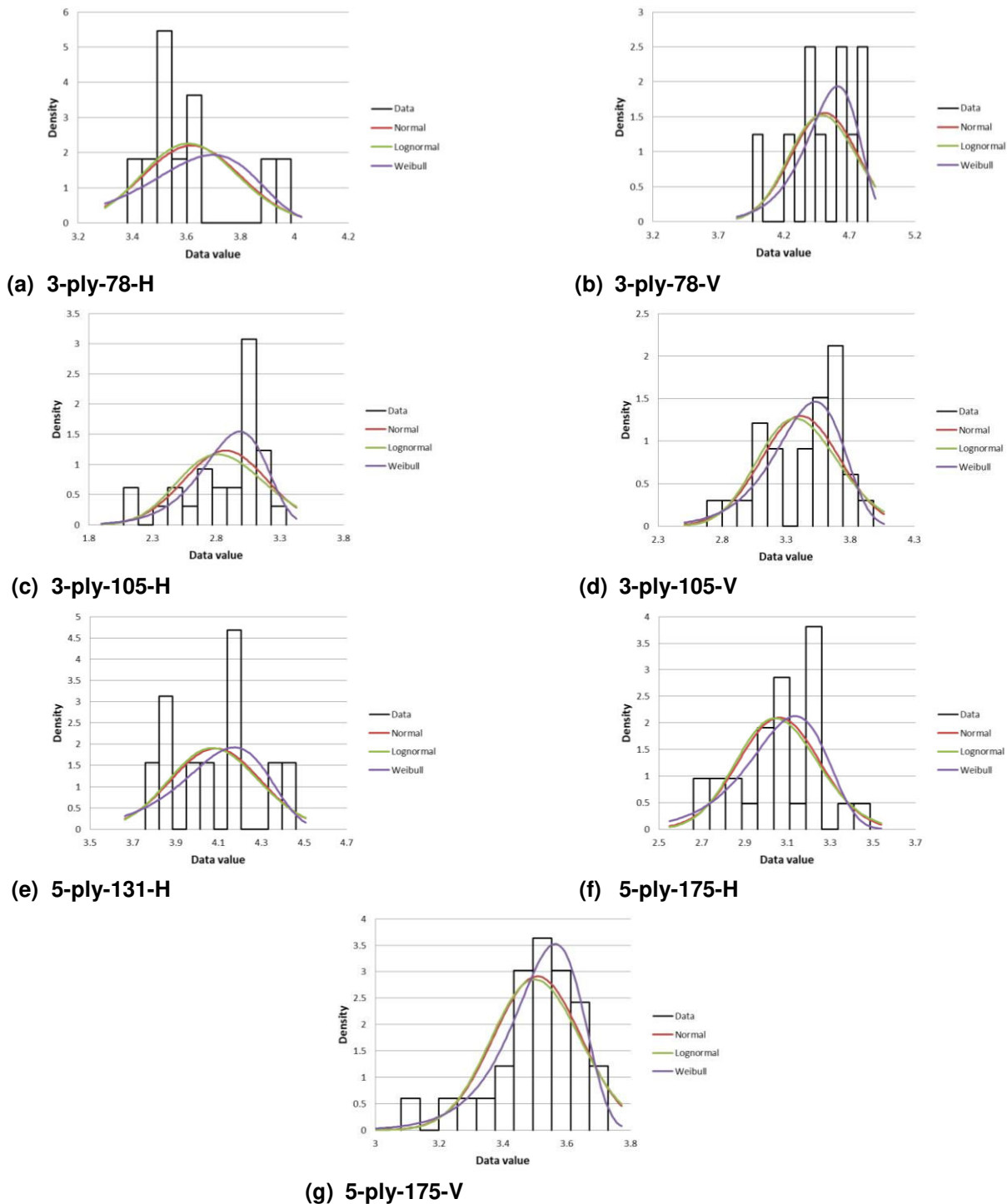


Figure 5 – Statistic distribution for each configuration with parametric analysis

**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<br>3-Ply-78 | Specific Gravity<br>(Kg/m <sup>3</sup> ) | Humidity<br>(%) |
|----|-------------------------|------------------------------------------|-----------------|
| 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            |
|    | <b>Minimum</b>          | <b>501.2</b>                             | <b>12.6</b>     |
|    | <b>Maximum</b>          | <b>546.0</b>                             | <b>18.3</b>     |
|    | <b>Mean</b>             | <b>521.2</b>                             | <b>14.6</b>     |
|    | <b>Std. Dev.</b>        | <b>13.49</b>                             | <b>1.86</b>     |
|    | <b>COV (%)</b>          | <b>2.6</b>                               | <b>12.7</b>     |

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

| #  | Specimen ID<br>3-Ply-78 | Specific Gravity<br>(Kg/m <sup>3</sup> ) | Humidity<br>(%) |
|----|-------------------------|------------------------------------------|-----------------|
| 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            |
|    | <b>Minimum</b>          | <b>472.8</b>                             | <b>12.4</b>     |
|    | <b>Maximum</b>          | <b>521.9</b>                             | <b>20.8</b>     |
|    | <b>Mean</b>             | <b>502.7</b>                             | <b>14.4</b>     |
|    | <b>Std. Dev.</b>        | <b>18.37</b>                             | <b>2.41</b>     |
|    | <b>COV (%)</b>          | <b>3.7</b>                               | <b>16.8</b>     |

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

| #  | Specimen ID<br>3-Ply-105 | Specific Gravity<br>(Kg/m <sup>3</sup> ) | Humidity<br>(%) |
|----|--------------------------|------------------------------------------|-----------------|
| 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            |
|    | <b>Minimum</b>           | <b>464.1</b>                             | <b>11.5</b>     |
|    | <b>Maximum</b>           | <b>546.1</b>                             | <b>13.9</b>     |
|    | <b>Mean</b>              | <b>496.5</b>                             | <b>12.5</b>     |
|    | <b>Std. Dev.</b>         | <b>20.38</b>                             | <b>0.67</b>     |
|    | <b>COV (%)</b>           | <b>4.1</b>                               | <b>5.4</b>      |

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

| #  | Specimen ID<br>3-Ply-105 | Specific Gravity<br>(Kg/m <sup>3</sup> ) | Humidity<br>(%) |
|----|--------------------------|------------------------------------------|-----------------|
| 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            |
|    | <b>Minimum</b>           | <b>472.1</b>                             | <b>11.6</b>     |
|    | <b>Maximum</b>           | <b>517.5</b>                             | <b>13.8</b>     |
|    | <b>Mean</b>              | <b>499.3</b>                             | <b>12.7</b>     |
|    | <b>Std. Dev.</b>         | <b>13.38</b>                             | <b>0.66</b>     |
|    | <b>COV (%)</b>           | <b>2.7</b>                               | <b>5.2</b>      |

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

| #  | Specimen ID<br>5-Ply-131 | Specific Gravity<br>(Kg/m <sup>3</sup> ) | Humidity<br>(%) |
|----|--------------------------|------------------------------------------|-----------------|
| 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            |
|    | <b>Minimum</b>           | <b>482.5</b>                             | <b>11.5</b>     |
|    | <b>Maximum</b>           | <b>552.6</b>                             | <b>12.2</b>     |
|    | <b>Mean</b>              | <b>515.0</b>                             | <b>11.8</b>     |
|    | <b>Std. Dev.</b>         | <b>18.36</b>                             | <b>0.25</b>     |
|    | <b>COV (%)</b>           | <b>3.6</b>                               | <b>2.1</b>      |

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

| # | Specimen ID<br>5-Ply-131 | Specific Gravity<br>(Kg/m <sup>3</sup> ) | Humidity<br>(%) |
|---|--------------------------|------------------------------------------|-----------------|
| 1 | V1                       | 534.2                                    | 11.4            |
| 2 | V2                       | 516.4                                    | 11.3            |
| 3 | V3                       | 490.0                                    | 11.5            |
|   | <b>Mean</b>              | <b>513.6</b>                             | <b>11.4</b>     |

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

| #  | Specimen ID<br>5-Ply-175 | Specific Gravity<br>(Kg/m <sup>3</sup> ) | Humidity<br>(%) |
|----|--------------------------|------------------------------------------|-----------------|
| 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            |
|    | <b>Minimum</b>           | <b>418.6</b>                             | <b>11.9</b>     |
|    | <b>Maximum</b>           | <b>551.3</b>                             | <b>13.8</b>     |
|    | <b>Mean</b>              | <b>492.7</b>                             | <b>12.7</b>     |
|    | <b>Std. Dev.</b>         | <b>24.66</b>                             | <b>0.50</b>     |
|    | <b>COV (%)</b>           | <b>5.0</b>                               | <b>3.9</b>      |

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

| #  | Specimen ID<br>5-Ply-175 | Specific Gravity<br>(Kg/m <sup>3</sup> ) | Humidity<br>(%) |
|----|--------------------------|------------------------------------------|-----------------|
| 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            |
|    | <b>Minimum</b>           | <b>460.6</b>                             | <b>12.1</b>     |
|    | <b>Maximum</b>           | <b>518.7</b>                             | <b>13.5</b>     |
|    | <b>Mean</b>              | <b>491.1</b>                             | <b>12.9</b>     |
|    | <b>Std. Dev.</b>         | <b>16.77</b>                             | <b>0.38</b>     |
|    | <b>COV (%)</b>           | <b>3.4</b>                               | <b>3.0</b>      |

## 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



H7



H8



H9



H10

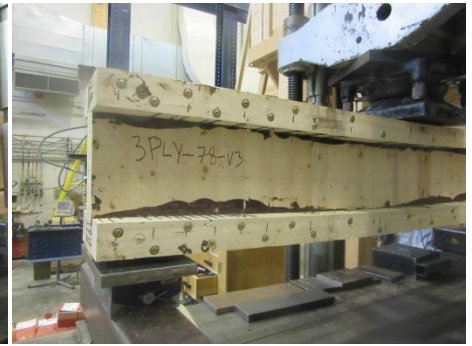
### 3-Ply-78-V



V1



V2



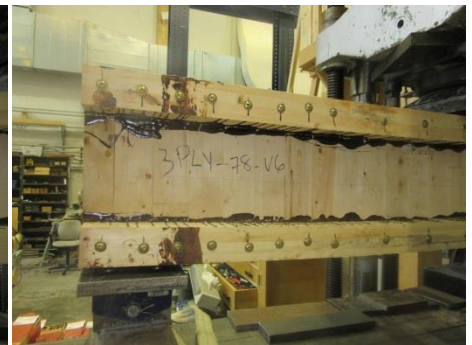
V3



V4



V5



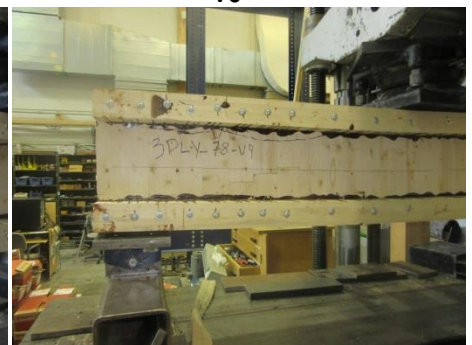
V6



V7



V8



V9



V10

### 3-Ply-105-H



H1



H2



H3



H4



H5



H6



H7



H8



H9



H10



H11



H12

### 3-Ply-105-H (continued)



H13



H14



H15



H16



H17



H18



H19



H20



H21



H22



H23



H24

### 3-Ply-105-H (continued)



H25



H26



H27

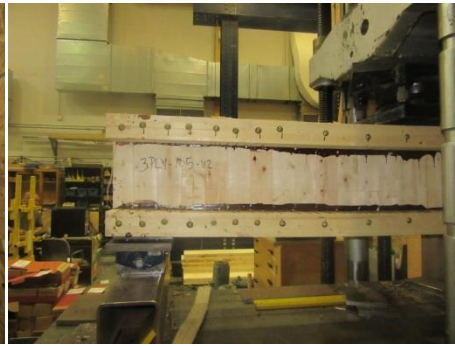


H28

### 3-Ply-105-V



V1



V2



V3



V4



V5



V6



V7



V8



V9



V10



V11

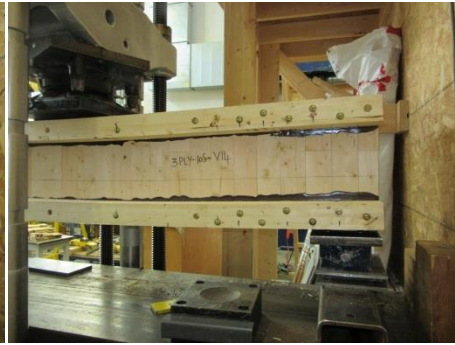


V12

### 3-Ply-105-V (continued)



V13



V14



V15



V16



V17



V18



V19



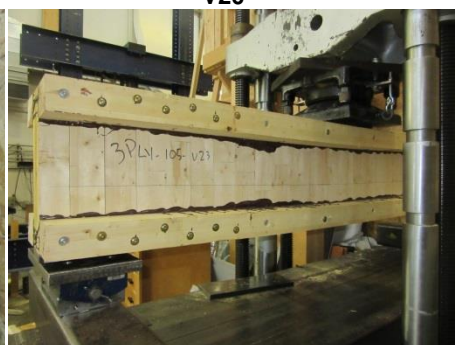
V20



V21



V22



V23



V24

**3-Ply-105-V (continued)**



**V25**



**V26**



**V27**

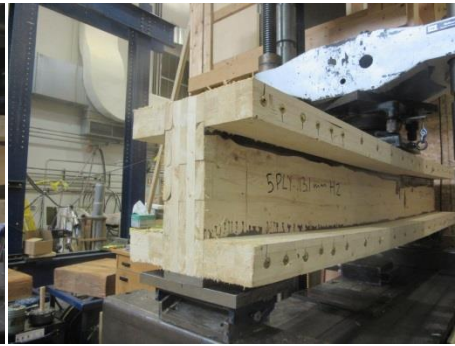


**V28**

## 5-Ply-131-H



H1



H2



H3



H4



H5



H6



H7



H8



H9



H10

## 5-Ply-131-V



V1



V2



V3

## 5-Ply-175-H



H2



H3



H4



H5



H6



H7



H8



H9



H10



H11-a



H11-b



H12

5-Ply-175-H (continued)



H13



H14



H15



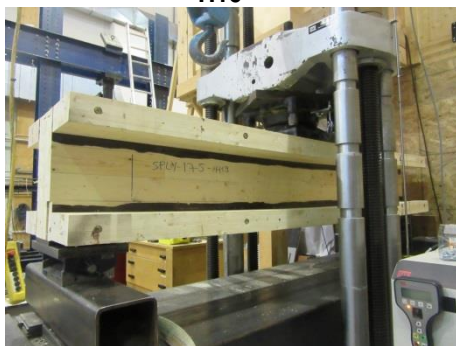
H16



H17



H18



H19



H20



H21



H22



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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