STRUCTURAL PERFORMANCE EVALUATION OF CLT WALL-SEGMENT/COLUMNS UNDER CENTRIC AND ECCENTRIC LOADINGS

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Structural Performance Evaluation of CLT Wall-Segment/Columns Under Centric and Eccentric Loadings

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1 Summary

This report presents the results of 15 tests of CLT wall-segment and/or columns that were conducted using the NRC high-capacity load column furnace under no heat conditions with centric and eccentric loading. FPInnovations and the Canadian Wood Council will use the data from these tests for the validation of CSA O86 combined stress design equations. The results of the 15 tests are also provided on a USB portable drive as part of the project deliverables.

The development of a validated combined axial and bending design equation for the CSA O86 Engineering Design in Wood standard will result in assuring the CSA O86 Technical Committee and the engineering community that the designs will effectively resist the anticipated loads for mid- to high-rise CLT walls for massive timber buildings.

While not part of this project, a copy of the rationale for the proposed interaction equation for combined bending and compressive axial loads that was prepared by the FPInnovations and Canadian Wood Council and submitted to the CSA O86 Technical Committee is also included in this report.
2 Acknowledgements

The authors are grateful to Patrice Leroux, Robert Berzins, Eric Gibbs, Pier-Simon Lafrance and Karl Gratton (NRC) for conducting the tests. Also, the authors are grateful to Nordic Engineered Wood, Structurlam, Canadian Wood Council and NRCan for their financial contributions and to FPInnovations for the valuable assistance during the testing program.
Table of Contents

1 Summary i
2 Acknowledgements ii
3 Introduction 1
4 Project Objective 1
5 Test Apparatus 1
6 Description of Test Specimens 2
   6.1 Test Specimen End Brackets 3
   6.2 Load End Rotating System 3
   6.3 Test Configurations 4
7 Test Conditions and Procedures 6
8 Instrumentations 6
9 Test Results 6
10 Summary of Results 6
11 References 6
12 Appendix A (Test Results- Nordic Engineered Wood Specimens) 7
13 Appendix B (Test Results – Structurlam Specimens) 16
14 Appendix C (Photos-Test Specimen at Failure Time for Nordic Engineered Wood) 24
15 Appendix D (Photos-Test Specimen at Failure Time for Structurlam) 33
16 Appendix E (Files Name on USB Portable Drive) 42
17 Appendix F (Rationale for Proposed Interaction Equation for Combined Bending and Compressive Axial Loads) 45
3 Introduction

This report presents the results of the collaborative research project between NRC, NRCan, Nordic Engineering Wood, Structurlam and the Canadian Wood Council for the evaluation of structural performance of CLT wall-segments and/or columns under centric and eccentric loadings.

For massive timber buildings made of structural CLT walls, as the case with any other buildings, the vertical loads of the walls are higher at the lower storeys. Therefore, the higher the number of storeys, the higher the axial load in the CLT walls of the first storey. In order to evaluate the structural load capacity of CLT walls of mid- to high-rise buildings, a testing facility with a substantially high load capacity is required. NRC has such a unique testing facility which made the execution of this project feasible.

CSA O86, the standard on “Engineering design in wood” [1], provides an equation for combined axial and bending forces on a wood member which had to be validated for the newly introduced CLT buildings. There is currently a need by the CLT industry to develop experimental data on the structural performance evaluation of CLT wall-segment/columns under centric and eccentric loadings to either support the current design approach or modify the equation for design with CLT. The development of a validated design equation will result in helping engineers to design CLT buildings with the same confidence as with other wood members (i.e. lumber, glulam, etc.).

4 Project Objective

The objective of this study is to produce data through testing of CLT wall-segments and columns using centric and eccentric loading elements to support validation of the CSA O86 combined stress design equation.

5 Test Apparatus

The NRC facility shown in Figure 1 is one of the largest column furnaces in the world and the only one in North America capable of testing a full-scale loaded column. The furnace can apply axial loads up to 9790 kN (2200 kips), lateral loads up to 110 kN (25 kips) in the North-South direction, and lateral loads up to 310 kN (70 kips) in the East-West direction, with or without fire loads. In addition, the load cells can be equipped with rotating (i.e. pinned) end plates to develop the appropriate column-end restraint conditions. In this project, the column furnace was used without fire load (i.e. under no heat conditions). Details on the NRC column test facility are giving in Ref. [2].
6 Description of Test Specimens

Fifteen wall/column test specimens were constructed: eight by Nordic Engineering Wood and seven by Structurlam. As an example, a 7 Plys sample is shown in Figure 2. The type and dimensions of CLT test specimens are given in Table 1 below:

Table 1. Test specimens.

<table>
<thead>
<tr>
<th>Lamination Grade</th>
<th>CLT Layers (PRG-320 thickness)</th>
<th>Total Columns</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1 – Nordic Engineered Wood CLT Columns</td>
<td>3 Plys $d_n = 105$ mm $d_m = 100$ mm</td>
<td>5</td>
</tr>
<tr>
<td>V2 – Structurlam CLT Columns (600 mm × d × 3600 mm)</td>
<td>5 Plys $d_n = 175$ mm $d_m = 169$ mm</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>7 Plys $d_n = 245$ mm Structurlam $d_m = 239$ mm Nordic $d_m = 241$ mm</td>
<td>8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Total Columns</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1</td>
<td>5</td>
</tr>
<tr>
<td>V2</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>2</td>
</tr>
</tbody>
</table>

$d_n$ – nominal
$d_m$ – measured
Figure 2. Example of Test specimen with 7 plies.

6.1 Test Specimen End Brackets

The end brackets for the attachment to the column apparatus end plates were designed by FPInnovations and fabricated by NRC to facilitate testing of specimens under centric and eccentric loading. Five holes were drilled at the column specimen ends and steel bolts with a diameter of 19 mm were used to facilitate the installation of the end brackets to test specimens, as shown in Figures. 3 to 6.

6.2 Load End Rotating System

The specimen end brackets, which can slide to provide eccentricity, were attached at the top and bottom of the loading system with a rotating angle mechanism to facilitate the specimen end to rotate due to the specimen bending when using eccentric loading conditions.

Figure 3. Test specimen bottom bracket and load end rotating system.
Figure 4. Test specimen top bracket.

Figure 5. Rotating top and bottom end plates.
6.3 Test Configurations

Table 2 lists the 15 test configurations which include, test date, number of Plys, and elements of combined stress equation: $e_0$ eccentricity, $\Delta_0$ initial wall imperfections in the mid-height, $\Delta_r$ deflection due to out-of-plane loading (i.e. bending due to wind for exterior walls) and ultimate load at failure.
Table 2. Test Configurations.

<table>
<thead>
<tr>
<th>Test Date</th>
<th>Test No.</th>
<th>CLT Specimens</th>
<th>Eccentricities$^{(1)}$</th>
<th>Ultimate Load (Pu) kN</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Grade</td>
<td>Plys</td>
<td>$e_0$</td>
</tr>
<tr>
<td>Jan 15, 2015</td>
<td>E1-T2</td>
<td>E1</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>Feb 5, 2015</td>
<td>E1-T6</td>
<td>E1</td>
<td>3</td>
<td>d/6 = 17 mm</td>
</tr>
<tr>
<td>Apr 14, 2015</td>
<td>E1-T7</td>
<td>E1</td>
<td>3</td>
<td>d/6 = 17 mm repeat</td>
</tr>
<tr>
<td>Jan 20, 2015</td>
<td>E1-T4</td>
<td>E1</td>
<td>3</td>
<td>d/3 = 34 mm</td>
</tr>
<tr>
<td>Apr 15, 2015</td>
<td>E1-T8</td>
<td>E1</td>
<td>3</td>
<td>d/2 = 52 mm</td>
</tr>
<tr>
<td>Jan 13, 2015</td>
<td>V2-T1</td>
<td>V2</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>Mar 18, 2015</td>
<td>V2-T5</td>
<td>V2</td>
<td>5</td>
<td>d/10 = 17 mm</td>
</tr>
<tr>
<td>Feb 2, 2015</td>
<td>V2-T3</td>
<td>V2</td>
<td>5</td>
<td>d/6 = 29 mm</td>
</tr>
<tr>
<td>Jan 16, 2015</td>
<td>V2-T2</td>
<td>V2</td>
<td>5</td>
<td>d/3 = 58 mm</td>
</tr>
<tr>
<td>Mar 17, 2015</td>
<td>V2-T4</td>
<td>V2</td>
<td>5</td>
<td>d/2 = 87 mm</td>
</tr>
<tr>
<td>Jan 8, 2015</td>
<td>E1-T1</td>
<td>E1</td>
<td>7</td>
<td>0</td>
</tr>
<tr>
<td>Jan 19, 2015</td>
<td>E1-T3</td>
<td>E1</td>
<td>7</td>
<td>d/3 = 80 mm</td>
</tr>
<tr>
<td>Feb 4, 2015</td>
<td>E1-T5</td>
<td>E1</td>
<td>7</td>
<td>d/6 = 40 mm</td>
</tr>
<tr>
<td>Mar 19, 2015</td>
<td>V2-T6</td>
<td>V2</td>
<td>7</td>
<td>d/9 = 25 mm</td>
</tr>
<tr>
<td>Mar 20, 2015</td>
<td>V2-T7</td>
<td>V2</td>
<td>7</td>
<td>d/2 = 122 mm</td>
</tr>
</tbody>
</table>

1. Note: (See plot) It would appear that with pinned ends rotating (free bending), the specimen was maintaining the load shown. When the rotation of the pins bottomed out (max. 4.9°) for this slender 3 lam specimen, it stiffened and continued to support the load as per the graph. These tests were repeated with modified end plates to validate maximum load carrying capacity.
2. Due to E1-T4 end rotation beyond 4.9°, the end plates were machined to allow rotation to 10-11° for the final two 3 lam specimens with maximum eccentricity.
7 Test Conditions and Procedures

No standard test procedure was considered in these 15 tests, however, an applied 30 psi load before test to make a contact between the specimen and the top and bottom load plates, and then an axial displacement rate of 2 mm/min, was used in all tests until specimen failure. The maximum rotation angle for the top and bottom plate was 4.9 degrees for all tests, except for Tests No. E1-T7 and E1-T8, where the maximum rotation angle was 10.4 degrees.

8 Instrumentations

Three instruments were used: one to measure the center displacement at mid height, the second to measure the rotation angle of the load end rotating system due to specimen bending and the third to measure the axial displacement due to loading.

9 Test Results

The test results of the applied load, specimen center and axial displacement, as well as the angle rotation for the eight Nordic Engineering Wood and seven Structurlam specimens, are given in graphical form in Appendix A and B, respectively. Photos of the test specimens at failure time for Nordic Engineered Wood and Structurlam are given in Appendix C and D, respectively. The data measured for the axial and centre displacement, top and bottom angle rotation as a result of specimen bending and specimen resistance load due to a displacement rate of 2 mm/min; photos taken before and after the test, as well as 3 video recordings during the test are given, due to the size of the files, on a USB portable drive and constitute a part of this report. The names of the test files on the USB drive are presented in Appendix E.

The data from these tests, which are needed for the validation of the CSA O86 combined stress design equation, were analyzed by FPInnovations and the Canadian Wood Council and submitted to the CSA O86 Technical Committee [3]. The analysis, not part of this project agreement with NRC, is presented in Appendix F.

10 Summary of Results

This report presents the results of 15 tests of CLT wall-segment and/or columns that were conducted using the NRC high-capacity load column furnace under no heat conditions with centric and eccentric loading. FPInnovations and the Canadian Wood Council will use the data from these tests for the validation of CSA O86 combined stress design equations. The results of the 15 tests are also provided on a USB portable drive as part of the project deliverables.

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11 REFERENCES

Appendix A (Test Results- Nordic Engineered Wood Specimens)
Figure A1. Results of Test E1-T1 (CLT 7 ply and no offset).
Figure A2. Results of Test E1-T2 (CLT 3 ply and no offset).
Figure A3. Results of Test E1-T3 (CLT 7 ply and 80 mm offset).
Figure A4. Results of Test E1-T4 (CLT 3 ply and 34 mm offset).
Figure A5. Results of Test E1-T5 (CLT 7 ply and 40 mm offset).
Figure A6. Results of Test E1-T6 (CLT 3 ply and 17 mm offset).
Figure A7. Results of Test E1-T7 (CLT 3 ply and 17 mm offset).
Figure A8. Results of Test E1-T8 (CLT 3 ply and 52 mm offset).
13 Appendix B (Test Results – Structurlam Specimens)
Figure B1. Results of Test V2-T1 (CLT 5 ply and no offset).
Figure B2. Results of Test V2-T2 (CLT 5 ply and 58 mm offset).
Figure B3. Results of Test V2-T3 (CLT 5 ply and 29 mm offset).
Figure B4. Results of Test V2-T4 (CLT 5 ply and 87 mm offset).
Figure B5. Results of Test V2-T5 (CLT 5 ply and 17 mm offset).
Figure B6. Results of Test V2-T6 (CLT 7 ply and 25 mm offset).
Figure B7. Results of Test V2-T7 (CLT 7 ply and 122 mm offset).
Appendix C (Photos—Test Specimen at Failure Time for Nordic Engineered Wood)
Figure C1. Photos at failure time for Test E1-T1 (CLT 7 ply and no offset).
Figure C2. Photos at failure time for Test E1-T2 (CLT 3 ply and no offset).
Figure C3. Photos at failure time for Test E1-T3 (CLT 7 ply and 80 mm offset).
Figure C4. Photos at failure time for Test E1-T4 (CLT 3 ply and 34 mm offset).
Figure C5. Photos at failure time for Test E1-T5 (CLT 7 ply and 40 mm offset).
Figure C6. Photos at failure time for Test E1-T6 (CLT 3 ply and 17 mm offset).
Figure C7. Photos at failure time for Test E1-T7 (CLT 3 ply and 17 mm offset).
Figure C8. Photos at failure time for Test E1-T8 (CLT 3 ply and 52 mm offset).
Appendix D (Photos-Test Specimen at Failure Time for Structurlam)
Figure D1. Photos at failure time for Test V2-T1 (CLT 5 ply and no offset).
Figure D2. Photos at failure time for Test V2-T2 (CLT 5 ply and 58 mm offset).
Figure D3. Photos at failure time for Test V2-T3 (CLT 5 ply and 29 mm offset).
Figure D4. Photos at failure time for Test V2-T4 (CLT 5 ply and 87 mm offset).
Figure D5. Photos at failure time for Test V2-T5 (CLT 5 ply and 17 mm offset).
Figure D6. Photos at failure time for Test V2-T6 (CLT 7 ply and 25 mm offset).
Figure D7. Photos at failure time for Test V2-T7 (CLT 7 ply and 122 mm offset).
Table E1 below presents the file names for the 15 tests.
Table E1. USB Portable Drive file names.

<table>
<thead>
<tr>
<th>Test Date</th>
<th>Test No.</th>
<th>CLT Grade</th>
<th>Lams</th>
<th>$e_0$</th>
<th>Specimen Supplied by</th>
<th>File Name in USB Portable Drive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan 15, 2015</td>
<td>E1-T2</td>
<td>E1</td>
<td>3</td>
<td>0</td>
<td>Nordic</td>
<td>20150115_Test-2_3-Ply_NoOffset</td>
</tr>
<tr>
<td>Feb 5, 2015</td>
<td>E1-T6</td>
<td>E1</td>
<td>3</td>
<td>$d/6 = 17$ mm</td>
<td>Nordic</td>
<td>20150205_Test-6_3-Ply_17mm</td>
</tr>
<tr>
<td>Apr 14, 2015</td>
<td>E1-T7</td>
<td>E1</td>
<td>3</td>
<td>$d/6 = 17$ mm</td>
<td>Nordic</td>
<td>20150414_Test-7_3-Ply_17mm</td>
</tr>
<tr>
<td>Jan 20, 2015</td>
<td>E1-T4</td>
<td>E1</td>
<td>3</td>
<td>$d/3 = 34$ mm</td>
<td>Nordic</td>
<td>20150120_Test-4_3-Ply_34mm</td>
</tr>
<tr>
<td>Apr 15, 2015</td>
<td>E1-T8</td>
<td>E1</td>
<td>3</td>
<td>$d/2 = 52$ mm</td>
<td>Nordic</td>
<td>20150415_Test-8_3-Ply_52mm</td>
</tr>
<tr>
<td>Jan 13, 2015</td>
<td>V2-T1</td>
<td>V2</td>
<td>5</td>
<td>0</td>
<td>Structurlam</td>
<td>20150113_Test-1_5-Ply_NoOffset</td>
</tr>
<tr>
<td>Mar 18, 2015</td>
<td>V2-T5</td>
<td>V2</td>
<td>5</td>
<td>$d/10 = 17$ mm</td>
<td>Structurlam</td>
<td>20150318_Test-5_5-Ply_17mm</td>
</tr>
<tr>
<td>Feb 2, 2015</td>
<td>V2-T3</td>
<td>V2</td>
<td>5</td>
<td>$d/6 = 29$ mm</td>
<td>Structurlam</td>
<td>20150202_Test-3_5-Ply_29mm</td>
</tr>
<tr>
<td>Jan 16, 2015</td>
<td>V2-T2</td>
<td>V2</td>
<td>5</td>
<td>$d/3 = 58$ mm</td>
<td>Structurlam</td>
<td>20150116_Test-2_5-Ply_58mm</td>
</tr>
<tr>
<td>Mar 17, 2015</td>
<td>V2-T4</td>
<td>V2</td>
<td>5</td>
<td>$d/2 = 87$ mm</td>
<td>Structurlam</td>
<td>20150317_Test-4_5-Ply_87mm</td>
</tr>
<tr>
<td>Jan 8, 2015</td>
<td>E1-T1</td>
<td>E1</td>
<td>7</td>
<td>0</td>
<td>Nordic</td>
<td>20150108_Test-1_7-Ply_NoOffset</td>
</tr>
<tr>
<td>Jan 19, 2015</td>
<td>E1-T3</td>
<td>E1</td>
<td>7</td>
<td>$d/3 = 80$ mm</td>
<td>Nordic</td>
<td>20150119_Test-3_7-Ply_80mm</td>
</tr>
<tr>
<td>Feb 4, 2015</td>
<td>E1-T5</td>
<td>E1</td>
<td>7</td>
<td>$d/6 = 40$ mm</td>
<td>Nordic</td>
<td>20150204_Test-5_7-Ply_40mm</td>
</tr>
<tr>
<td>Mar 19, 2015</td>
<td>V2-T6</td>
<td>V2</td>
<td>7</td>
<td>$d/9 = 25$ mm</td>
<td>Structurlam</td>
<td>20150319_Test-6_7-Ply_25mm</td>
</tr>
<tr>
<td>Mar 20, 2015</td>
<td>V2-T7</td>
<td>V2</td>
<td>7</td>
<td>$d/2 = 122$ mm</td>
<td>Structurlam</td>
<td>20150320_Test-7_7-Ply_122mm</td>
</tr>
</tbody>
</table>
17 Appendix F (Rationale for Proposed Interaction Equation for Combined Bending and Compressive Axial Loads)

The information presented in this Appendix F is a copy of the analysis made by FPInnovations and Canadian Wood Council which was submitted to the CSA O86 Technical Committee for consideration. FPInnovations and the CWC have authorized NRC to include a copy of the “Rationale for Proposed Interaction Equation for Combined Bending and Compressive Axial Loads" in this report to show readers the outcomes from the NRC test data in this project.

“This appendix contains the analysis for the design equation validations that was submitted to the CSA O86 Technical Committee. Although not part of the current report scope, the appendix serves to present the full extent of the scope of work for presentation to the CSA O86 TC.

Mr. Gary Williams, Chair of CSA O86, and Mr. Steve Boyd, Vice chair of CSA O86, have approved the inclusion of such analysis as an appendix to the current report (please see enclosed email). NRC requires that the consortium members: Nordic, Structurlam, NRCan, and CWC shall treat this entirety of this report as a confidential document.”
“Rationale for Proposed Interaction Equation for Combined Bending and Compressive Axial Loads

CLT panels subject to combined bending and compressive axial loads shall be designed to satisfy the interaction equation:

\[
\frac{P_f}{P_r} + \frac{M_f}{M_r} \left[ 1 - \frac{1}{P_{f_v} \frac{P_E}{(GA)_{eff}}} \right] \leq 1
\]

where

\( P_f \) = factored compressive axial load
\( P_r \) = factored compressive resistance under axial load, calculated in accordance with Clause 8.5.5.4
\( M_f \) = factored bending moment
\( M_r \) = factored bending moment resistance, calculated in accordance with Clause 8.5.3
\( P_{f_v} \) = Euler buckling load in the plane of the applied bending moment taking into account shear deformation

\[
= \frac{P_E}{1 + \frac{\kappa \cdot P_E}{(GA)_{eff}}} 
\]

where

\( P_E \) = Euler Buckling load in the plane of the applied moment (Clause 7.5.12) calculated using \( I_{eff} \) and \( E_{os} \) of laminations parallel to the axial load
\( \kappa \) = form factor
\( = 1.2 \) for rectangular sections
\( (GA)_{eff} \) = effective shear-through-thickness rigidity of CLT panel accounting for all layers, N (Clause 8.4.3.1)

Rationale:

In order to validate the proposed interaction equation, 13 specimens in total were tested under combined bending and compressive axial loads. The bending moment is applied through imposing the compressive load, \( P_f \), at an eccentricity, \( e \) (see specimen configurations in Appendix I). The 13 specimen covered the following configurations:

- two grades, E1 and V2
- three layup, 3-ply, 5-ply and 7-ply, and
- five eccentricity, \( e = 0, d/10, d/6, d/3, \) and \( d/2 \).

Due to budget limitations, for a certain grade of certain lay-up, only one specimen was tested at a specific eccentricity. The details can be found in the NRC report (currently in preparation).

The test data for pure bending were collected from FPInnovations and manufacturers which included E1-3 ply, custom-5 ply (S-P-F 1650f MSR (L) and S-P-F No. 3/Stud (T) lumber grades) and E1-7 ply. There was one group of specimens tested in pure bending for E1-3 ply, five groups for custom-5 ply and one group for E1-7 ply, with ten specimens in each group.

Test data \( (P_f, M_f) \) were compared with calculations using the proposed interaction equation.

Curves for calculated values: The following steps explain how the calculated values were obtained.
Step 1:
Calculated factored axial compressive and moment resistances \((P_r\) and \(M_r\)) based on the proposed equations.

Step 2:
Set \(P_f = (0, 0.1, 0.2, 0.3 \ldots 1) \times P_r\);

Step 3:
Back calculate \(M_f\) based on the following interaction equation:

\[
\frac{P_f}{P_r} + \frac{M_f}{M_r} \left[ 1 - \frac{P_f}{P_{E,V}} \right] = 1
\]

Step 4:
Plot \((M_f, P_f)\) for calculated values.

Curves for test values:
The calculated \(P_r\) and \(M_r\) and maximum \((M_f, P_f)\) using the interaction equation are the factored resistance based on the specified strength derived from 5th percentile and standard term load duration. In order to compare with the calculated values, the test values were converted using standard conversion procedure as follows:

For pure bending test data:

1. \(5^{th}\) percentile = Mean – 2.104*standard deviation  
   \((As per Table 3 of ASTM D2915 for n=10 samples)\)
   Specified bending moment resistance = \(5^{th}\) percentile * (reliability normalization factor B) *  
   (standard term conversion factor 0.8)
   \((As per “Standard Practice relating Specified Strength to Characteristic Structural Properties”)\)

2. There was only one group of E1-3 ply with 10 specimens and the specified bending moment is therefore the pure bending moment used for E1-3 ply.

There were five groups of custom-5 ply with 10 specimens in each group, with the longitudinal layers being S-P-F 1650f MSR and transverse layers being S-P-F No. 3/Stud lumber grades. However, each group has a different COV and therefore the data points could not be compiled, and the average specified bending moment of these five groups was calculated and taken as the pure bending moment used for this custom-5 ply. There was no bending test data for V2-5 ply. Therefore, it was determined by converting the bending test data for custom-5 ply multiplied by the ratio of the bending moment resistance of these two grades/layups calculated based on the mechanical model.
There was only one group of E1-7 ply with 10 specimens and the specified bending moment is therefore the pure bending moment used for E1-7 ply. There was no bending test data for V2-7 ply, so it was determined by converting the bending test data for E1-7 ply multiplied by the ratio of the bending moment resistance of these two grades/layups calculated based on the mechanical model.

3. Factored bending moment resistance = 0.9 * Specified bending moment resistance

**For pure axial compressive loads and the maximum \((P_f, M_f)\) in combined loading:**

For a certain grade of layup, only one specimen was tested at a specific eccentricity, these data were treated as mean value, and they were converted as follows:

1. from 10 minutes short term to standard term using a factor of 0.8;
2. from mean value to 5\(^{th}\) percentile using a factor of 1.25 for E1 grade and 1.55 for V2 grade. Note that those factors were obtained from the bending test data by calculating the average ratio of mean value to 5\(^{th}\) percentile for each grade;
3. to factored resistance by applying the resistance factor \(\emptyset = 0.8\).

Therefore, the \(P_f\) values obtained from NRC tests were converted using \((P_{f-test} \times 0.8 \times 0.8)\) (or divided by 1.55 for V2 grade). Please note that in order to get as much data points as possible out of limited number of specimens, the pure axial compression load for V2-7 ply (without eccentricity) was obtained from E1-7 ply, \(P_{f-test}\) at \(e=0\), multiplied by the ratio of the compressive resistance of these two grades/layups calculated based on the mechanical model.

As for \(M_f\), the factored moment was calculated as follows:

\[
M_f = P_f \times (e + \Delta_0 + \text{load cell offset})
\]

where \(e\) is the eccentricity, \(\Delta_0\) is the initial imperfection, and load cell offset caused by rotation.

The original test data for mean values, which were only adjusted from 10 minutes short term to standard term (i.e. times 0.80), were also plotted in the graph to illustrate the possible over-strength built in the design.

**Comparison**

The comparison were shown in the following Figures, where the horizontal axis is “unamplified” moment, i.e. the applied moment (\(P\times e\)), and the vertical axis indicates the axial compression load. The x-intercept indicates the pure bending moment resistance and the y-intercept indicates the pure axial compressive resistance. The proposed (unsquared) interaction equation is presented. For the purpose of comparison, the curves for interaction equation with squared term (which is the current one for sawn lumber and glulam), are also shown in the graphs for the various CLT grades and lay-ups tested.
Figure 1. Comparison between test and proposed interaction equation for E1-3 ply CLT column.

Figure 2. Comparison between test and proposed interaction equation for E1-7 ply CLT column.
Figure 3. Comparison between test and proposed interaction equation for V2-5 ply CLT column.

Figure 4. Comparison between test and proposed interaction equation for V2-7 ply CLT column.
Conclusions and discussions:

It can be seen that in general, the calculated values based on non-squared interaction equations fall under the converted test data, except for the pure bending moment resistance for E1-7ply with the difference of 6%. Considering there were only 10 specimens tested in pure bending for E1-7 ply, it can be argued that it is acceptable. There was no bending test data for V2-7ply and the X-intercept in Figure 4 was converted from E1-7 ply test data and therefore could be disregarded. There was also no bending test data for V2-5ply and the X-intercept in Figure 3 was converted from a custom-5 ply test data. Nevertheless, the test data for pure axial compressive resistance and combined bending and axial compression validate the “non-squared” interaction equation proposed herein. It is evident from the graphs above that the squared term interaction equation overestimates for E1-7 ply.
Appendix I

<table>
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<th>Eccentricities</th>
<th>e = 0</th>
<th>e = d/6</th>
<th>e = d/3</th>
<th>e = d/2</th>
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<td><img src="image3" alt="Diagram" /></td>
<td><img src="image4" alt="Diagram" /></td>
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</tbody>
</table>

Figure I.1. Specimen configurations with or without load eccentricities.”
Good morning Bruno,

Steve and I agree this is fine as long as Structurlam agrees with you that it will be held in confidence.

BTW, thank you again for your helpful participation at O86 in Vancouver.

Best, Gary

G

Hello Gary and Steve, it was great seeing you both at the CA O86 meeting in Vancouver.

We are finalizing the NRC Test Report for the CLT Axial Testing w/o eccentricity. For this Test Report to the clients, I would like to include the attached analysis document in an Appendix so that the clients see the benefits of their funding of the NRC test program. Also, the full extent of the scope of work for presentation to the CSA O86 TC.

The consortium clients were: Nordic, Structurlam, NRCAn, CWC and NRC. The CWC and Nordic have already seen the document since they attend CSA O86. However, Structurlam do not participate and I would like to show them the end result. I’m hoping that this will also help in the future when we may want to ask them to support additional CLT testing/research.

Let me know if you would allow us to provide this CSA O86 Poll Item document to our clients.

It would be in a separate Appendix and we would require that it remain confidential, it is likely that the test results will be treated confidentially as well by the clients.

For your consideration. Tks.

Bruno Di Lenardo, P.Eng.

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