EXPERIMENTAL PERFORMANCE TESTING OF CANTILEVER CROSS-LAMINATED TIMBER (CLT) DIAPHRAGM UNDER IN-PLANE SHEAR

Bibek Bhardwaj¹, Weichiang Pang², Douglas Rammer³, M. Omar Amini⁴, Steven E. Pryor⁵

ABSTRACT: This paper investigates the in-plane shear behavior of a full-scale 20 ft. x 20 ft. (6.1 m x 6.1 m) cantilever Cross Laminated Timber (CLT) diaphragm experimentally. The diaphragm consisted of eight 5 ft. x 10 ft. (1.5 m x 3 m) three ply CLT-panels connected to each other along the long edge by plywood surface splines with nails and connected along the short edge to glulams underneath with screws. The diaphragm was tested with a cyclic loading protocol. The ultimate capacity of the diaphragm exceeded the design capacity. Test results showed that sliding (slip along the loading direction) and rotation of CLT panels, caused by fastener deformations were the two major energy dissipation mechanisms. The strains measured on the top and bottom surfaces of CLT panels revealed a deep beam like effect, in which the edge CLT panels contributed significantly to resisting coupled tension and compression forces with little to no contribution from the CLT panels near the neutral axis. A comparison between the various contributions of diaphragm deflections computed using the latest code equation (2021 version of NDS) and that measured from the test suggested that a revision to the current diaphragm deflection equation may be necessary.

KEYWORDS: CLT Diaphragm Test, Cross-Laminated Timber, Glulam, NDS Deflection Equation, Cyclic Loading

1 INTRODUCTION

Cross Laminated Timber (CLT) is an engineered wood panel composed of layers of dimensional lumbers stacked and glued together in orthogonal directions. Such an arrangement of plies creates a two-way slab system with high dimensional stability [1]. Compared to steel and concrete, CLT has high strength to weight ratio. CLT is significantly lighter than steel and concrete (about 1/12 of the weight of steel and 1/5 of the weight of concrete of the same volume). On top of that, CLT offers added benefits such as cost-effectiveness, faster on-site construction and long-term sustainability, which makes it an ideal alternative to concrete and steel for certain building types, in particular, mid-rise construction.

The concept of CLT originated in the 1990s in Austria and Germany. The use of CLT has gained popularity in the North American construction market in the past decade. In the US, as the popularity of CLT continue to grow, standardization of the fabrication, testing and application of CLT products are needed. As of 2020, ANSI/APA PRG 320 provides product performance classes as well as requirements and test methods for quality assurance of performance rated CLT products. In 2015, the National Design Specification (NDS) for Wood construction introduced basic engineering design provisions specifically applied to CLT manufactured in accordance with APA PRG-320 (Chapter 10). The 2021 Special Design Provisions for Wind and Seismic (SPDWS) includes guidance for wind and seismic design of CLT shear walls and diaphragms. The International Code Council (ICC) has also approved the inclusion of three new construction types IV-A, IV-B and IV-C in the 2021 International Building Code (IBC) which will allow the use of mass timber or non-combustible materials in tall wood buildings. IBC 2021 will include provisions for up to 18 stories of Type IV-A construction for Business and Residential Occupancy class [2]. Other technical resources, such as the CLT Handbook also provide necessary technical information needed by engineers to safely design CLT structures.

Despite recent developments in CLT research, there is only a scant body of knowledge with regard to the actual performance of CLT diaphragms. The design provisions for CLT diaphragms under seismic and wind loads in current building codes such as the NDS lack supporting information from experiments when compared to that of the current light-frame wood diaphragm design

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provisions [3]. The reference design values for strength and shear published in the NDS for light-frame construction were determined through many full-scale diaphragm tests. At the time of writing this paper, there are only a handful of ongoing or completed full-scale CLT diaphragm experiments. The publications currently available do not comprehensively describe the lateral load resistance performance of CLT diaphragms. This paper presents and discusses the design and experimental results of a full-scale cantilever CLT-glulam composite diaphragm tested under a cyclic loading protocol.

2 BACKGROUND

With building owners’ preference toward open-floor layouts with little to no shear walls at the exterior wall lines, shear-core buildings have been gaining widespread popularity. On the other hand, emphasis on reducing the carbon footprint of buildings for long-term sustainability has led to increasing number of recent projects utilizing mass timber as the primary construction material [4]. Examples of tall mass timber buildings with open-floor plans include the T3 building in Minnesota and Brock Commons Tallwood house in Vancouver, British Columbia. A typical floor in a shear-core building cantilevers off from the central shear cores. The floor (cantilever diaphragm) is one of the major components of the lateral load resisting system of the building, in which it collects and drags lateral forces to the shear cores.

Several studies were carried out to quantify the strength and stiffness of CLT diaphragms. A 2D numerical model was developed to quantify the stiffness of CLT diaphragms using calibrated connection models obtained from small-scale connection tests [5]. A 16.4” x 14” cantilever CLT diaphragm constructed using metal surface splines with 16d nails as panel-to-panel connection in the direction of load was studied experimentally [6]. The diaphragm was supported by three 4x8 SPF dimension lumbers perpendicular to the direction of load, connected with screws (SDS screws by Simpson Strong-Tie). The outer two dimensional lumbers acted as tension and compression chords. Tension straps were not installed and the tensile forces were assumed to be transferred from the CLT to the chords (4x8 SPF lumbers) underneath via the SDS screws. The diaphragm was designed to fail in shear at the surface spline region. The test showed insufficient strength at the chord region where the SDS screws in the chord region failed and opened up the gap between adjacent panels at the splines thus leading to the failure at the splines due to inter-panel tension. In additional, several CLT connections tests were also carried out to supplement full-scale diaphragm tests. Tests on CLT connections have shown that fasteners contribute significantly to the ductile behavior of a CLT connection and are the primary energy dissipation mechanism [3]. Typically, a CLT panel is significantly more rigid than the fasteners used.

Since only a scant body of knowledge exists for cantilever CLT diaphragms, a full-scale CLT diaphragm test was performed at Clemson University (1) to verify the accuracy of the current diaphragm design methods, (2) to understand the fastener contribution to diaphragm strength and stiffness, (3) to verify the diaphragm chord design criteria, (4) to study the variation of strain across the depth of diaphragm, and (5) to collect full-scale test data for developing numerical (computer) models.

3 EXPERIMENTAL SETUP

3.1 DESCRIPTION OF CLT DIAPHRAGM

The test diaphragm was a 20 ft. x 20 ft. (6.1 m x 6.1 m) CLT-glulam composite diaphragm composed of eight 3-ply 5 ft. x 10 ft. (1.5 m x 3 m) V3 grade Southern Pine CLT panels. The panels were supported underneath across the long direction by three 20 ft. (6.1 m) long 20F-V4 Southern Pine glulam beams (Figure 1). The glulam beams were 11 in. (27.9 cm) deep. The outer glulam beams were 3-1/8 in. (7.9 cm) wide while the center glulam was 6 in. (15.2 cm) wide. The diaphragm cantilevered from a fixed support. Two rows of 1/2 in. (12.7 mm) lag screws spaced 6 in. (15.2 cm) on center were used to fasten the edge glulam to the fixed support. Wood screws (Simpson Strong-Tie SD2S22800DB) at 6 in. (15.2 cm) on-center were used to fasten CLT panels to the glulam beams underneath. The longitudinal edges of the CLT panels were connected using 1-7/16 in. (2.7 cm) thick Spruce Pine-Fir plywood surface splines with 16d nails at 3 in. (7.62 cm) on center.

![Figure 1: Plan of diaphragm layout](image)

Tension straps (Simpson Strong-Tie MSTC40) bridging across the middle glulam beam were used to carry tension force. Five tension straps were installed on each side, one tension strap per 2 x 6 (3.8 cm x 14 cm nominal) lumber composing the CLT panel, thus spanning the tension chords of diaphragm 27.5 in (69.8 cm) from each diaphragm edge. Custom-made hold-downs designed by Simpson Strong-Tie were used to carry the tension forces at the fixed end. The hold-downs were placed such that their centerline lied 10 in. (25.4 cm) from the edge of the diaphragm. The hold downs
were connected to the CLT with fifty-two ½ in. x 3.5 in. (12.7 mm x 88.9 mm) lag screws while they were tied down to concrete filled hollow steel sections (HSS) via threaded rods which were firmly attached to the rigid support. Casters were installed beneath the middle and free-end glulam beams to support the diaphragm vertically. The load was applied using a 150-kip (667 kN) actuator via a channel section connected to the free-end glulam by two rows of ½ in. (12.7 mm) lag screws spaced at 6 in. (15.2 cm) on center. A set of casters was installed on top of the CLT near the free end to prevent the diaphragm from buckling out of plane during loading.

3.2 DESIGN STRENGTH OF DIAPHRAGM COMPONENTS

The test diaphragm was designed in accordance to the provisions in the 2021 SDPWS of NDS [7] and the procedure outlined in a CLT diaphragm design white paper [8]. The ultimate LRFD (Load and Resistance Factor Design) strength of the diaphragm was computed using [7] and [8]. The diaphragm was designed such that the LRFD design strengths of hold-downs, tension straps and chord members were at least two times that of the diaphragm design strength. For this test diaphragm, the ultimate strength of the diaphragm was controlled by the capacity of the nailed surface spline. A summary of the LRFD strength of the diaphragm components is given in Table 1.

<table>
<thead>
<tr>
<th>Component</th>
<th>Design strength (kip / kN)</th>
<th>Design strength compared to nailed connection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Panel-Panel Nails</td>
<td>22.1 / 98.3</td>
<td>1:1</td>
</tr>
<tr>
<td>Panel-Glulam Screws</td>
<td>35.6 / 158.3</td>
<td>1.5:1</td>
</tr>
<tr>
<td>Tension Straps</td>
<td>28.5 / 126.7</td>
<td>2.3:1</td>
</tr>
<tr>
<td>Chord comp.</td>
<td>73.6 / 327.4</td>
<td>2.9:1</td>
</tr>
<tr>
<td>Hold-downs</td>
<td>126 / 560.4</td>
<td>5:1</td>
</tr>
</tbody>
</table>

The LRFD design strength of the diaphragm, governed by the nailed surface spline, was 22.1 kip (98 kN). The last column in Table 1 shows the ratios of the design strength of each component to the design strength of nailed surface spline.

3.3 INSTRUMENTATION AND DATA ACQUISITION

The instrumentation of the test diaphragm included 69 sensors – 40 strain gauges, 27 string pots and 2 load cells. To study the variation of strain along the diaphragm in the direction of loading, 32 strain gauges were installed at 30 in. from the fixed support as shown in Figures 3 and 4. 16 strain gauges were installed on the top ply of the CLT. Similarly, 16 strain gauges were installed on the bottom ply of the CLT. The top and bottom strain gauges were paired such that at each location instrumented with strain gauges, there were a pair strain gauges (one on the top surface and one on the bottom surface of the CLT panel). Note that hold-downs were installed on the top surface of the diaphragm (see Figure 2). The pairing of top and bottom strain gauges
was to investigate load path in the diaphragm and to study possible variation of strain across the thickness of CLT panels.

The strain gauges near the diaphragm edges were closely spaced as it was speculated that this region would show higher strains and rapid change in strain as a function of distance from the edge of the extreme tension or compression of the diaphragm, similar to that in a deep beam. Based on the same speculated deep beam behavior, the strain gauges near the center were spaced further apart. Only two pairs of strain gauges were installed for each panel near the center (see Figures 3 and 4). These strain gauges were installed on top of 1 in. x 8 in. (25.4 mm x 203 mm) x 0.005 in. (0.13 mm) thick metal shims. This was done to avoid the influence of localized irregularities in wood such as knots on the measured strains. 8 metal strain gauges were installed on the tension straps to study the variation of strain within the designed tension zone.

The strains were measured using Wheatstone bridge circuit. An input voltage of 6V was selected for the Wheatstone bridges to obtain a balance between heat generation and resolution of strain measurement. A higher input voltage would cause more heat generated at the strain gauges while low input voltage would lead to lower output voltage which would make it difficult for the data acquisition (DAQ) system to read the strain. The output voltages from the Wheatstone bridge were measured using the Measurement Computing 18-bit USB-1608G DAQ modules with differential configuration.

The TE Connectivity SP1 series string pots were used to track the relative displacements of various diaphragm components during load application as shown in Figures 5 and 6. String pots 1-8 were installed parallel to the glulam beams, beneath the CLT to track slips between CLT and glulam. String Pots 9-12 were placed on top of the diaphragm along the short edges of CLT panels to track separation of CLT panels due to rocking motion of the CLT panels. String pots 13-18 were placed at the long edges of CLT panels to track differential movements between the adjacent CLT panels (i.e. slips along the nailed surface spline connections). String pots 19 and 23 were installed on the hold-downs to track the uplift of the diaphragm with respect to the HSSs (fixed end supports). String pots 20 and 21 were used to track the diagonal displacements of the diaphragm. String pots 25, 22 and 24 were use to measure the relative displacements with respect to the ground and parallel to the direction of loading along the fixed-end, middle and free-end glulam beams, respectively. The string pot circuits were supplied with 15V input voltage and the output voltages were measured using the Measurement Computing USB-2633 DAQ.

Tokyo Measurement Lab KCM 500 Load cells were installed to measure the variation of tensile force in the hold-downs with respect to the applied force. The load cells had a capacity of 112.4 kip (500 kN) with an overload capacity of 150%. The load cell data were measured using the Measure Test Simulate (MTS) system, which was also used to record the actuator displacement and applied force during the test.

All the data for the diaphragm test were sampled at a rate of 20 Hz. All three types of data acquisition devices were synchronized using time signatures.

A digital camera was installed to capture the overall diaphragm deformed shape and relative motions of all components during load application (see Figure 17).

3.4 LOADING PROTOCOL

Cyclic loading based on the CUREE (Consortium of Universities for Research in Earthquake Engineering) protocol was used for this test, with a few modifications. The original CUREE protocol starts with 6 cycles at 5%
of reference displacement (Δref), known as initiation cycles. For the destructive test however, additional 5 cycles, each at 1% and 2.5% of Δref were introduced. This was done to ensure all the sensors picked up data and so that the test could be stopped before displacement reached high levels to rectify any instrumentation errors. The reference displacement (Δref) adopted for the CUREE cyclic loading protocol was 4 in., which was based on the results of a preliminary numerical model and the results observed in other diaphragm tests. In lack of prior test results for a CLT diaphragm with similar configuration, the results from a prior CLT diaphragm test [6] were used as a starting point for reference displacement estimation. A preliminary numerical model of the diaphragm was built using Timber3D, a Matlab based program for modelling wood structures [9]. Monotonic pushover analysis using Timber3D was performed on the diaphragm model to estimate the reference displacement. A loading rate of 0.1 in./sec was used for the initiation cycles and displacement up to 15% of Δref. The loading rate was then increased to 0.25 in/sec for cycles with peak displacements between 15% and 260% of Δref. The loading rate was then increased to 0.5 in/sec for cycles between 260% and 300% of Δref. Note that the test was terminated prior to reaching 300% of Δref due to failure of the diaphragm, which will be discussed in a later section of this paper. Table 2 shows the displacement loading protocol used for this test.

Table 2: Loading protocol displacement sequence

<table>
<thead>
<tr>
<th>Amplitude (%Δref)</th>
<th>Primary Cycle</th>
<th>Trailing Cycle (75% amplitude of Primary)</th>
<th>Disp. Rate (in/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5</td>
<td>-</td>
<td>0.1</td>
</tr>
<tr>
<td>2.5</td>
<td>5</td>
<td>-</td>
<td>0.1</td>
</tr>
<tr>
<td>5</td>
<td>6</td>
<td>-</td>
<td>0.1</td>
</tr>
<tr>
<td>7.5</td>
<td>1</td>
<td>6</td>
<td>0.1</td>
</tr>
<tr>
<td>10</td>
<td>1</td>
<td>6</td>
<td>0.1</td>
</tr>
<tr>
<td>20</td>
<td>1</td>
<td>3</td>
<td>0.1</td>
</tr>
<tr>
<td>30</td>
<td>1</td>
<td>3</td>
<td>0.25</td>
</tr>
<tr>
<td>40</td>
<td>1</td>
<td>2</td>
<td>0.25</td>
</tr>
<tr>
<td>70</td>
<td>1</td>
<td>2</td>
<td>0.25</td>
</tr>
<tr>
<td>100</td>
<td>1</td>
<td>2</td>
<td>0.25</td>
</tr>
<tr>
<td>120</td>
<td>1</td>
<td>2</td>
<td>0.25</td>
</tr>
<tr>
<td>140</td>
<td>1</td>
<td>2</td>
<td>0.25</td>
</tr>
<tr>
<td>160</td>
<td>1</td>
<td>2</td>
<td>0.25</td>
</tr>
<tr>
<td>180</td>
<td>1</td>
<td>2</td>
<td>0.25</td>
</tr>
<tr>
<td>200</td>
<td>1</td>
<td>2</td>
<td>0.25</td>
</tr>
<tr>
<td>220</td>
<td>1</td>
<td>2</td>
<td>0.25</td>
</tr>
<tr>
<td>240</td>
<td>1</td>
<td>2</td>
<td>0.25</td>
</tr>
<tr>
<td>260</td>
<td>1</td>
<td>2</td>
<td>0.5</td>
</tr>
<tr>
<td>280</td>
<td>1</td>
<td>2</td>
<td>0.5</td>
</tr>
<tr>
<td>300</td>
<td>1</td>
<td>2</td>
<td>0.5</td>
</tr>
</tbody>
</table>

4 EXPERIMENTAL TEST RESULTS

4.1 HYSTERESIS LOOP

Figure 7 shows the plot of actuator force versus displacement at the free-end of the cantilever diaphragm. Overall, the diaphragm exhibited near symmetrical behavior, with slightly higher stiffness on the negative displacement cycle (actuator pulling) than the positive (actuator pushing) cycle. The observed diaphragm peak force was 42.6 kips (189.5 kN) at 4.72 in (11.9 cm) which was 1.93 times than of the LRFD capacity (22.1 kip or 98 kN). The peak load for the overall test was observed during the negative cycle. The peak load for the positive cycle was 42.0 kips (186.8 kN) at 5.57 in. (14.1 cm). The difference between two peak forces were 0.6 kips (2.7 kN) or 1.4% whereas the difference between corresponding displacement at peak forces were 0.85 in. (2.2 cm) or 16.5%.

![Figure 7: Hysteresis loop for destructive test](image)

4.2 STRAIN VARIATION ACROSS DIAPHRAGM

Figures 8 and 9 show the variation of strain across the diaphragm from extreme tension edge to extreme compression edge at two load levels (20 kip and 35 kip). The strains at load of 20-kip correspond to the LRFD design level loading, whereas the strains at 35-kip load correspond to post design level loading. On the tension side for both positive and negative cycles, the top ply of the CLT developed substantial tension while the bottom ply developed some compression. On the compression side, both the top and bottom plies of CLT developed compression. The observed behavior of only the top ply exhibited tension strain was attributed to the installation of the hold-downs on top of the diaphragm with hold-down screws fastened directly to the top ply of CLT panels. Additionally, the middle ply with the grain of lumber oriented perpendicular to the tension load direction limited the transfer of tension forces from the top ply to the bottom ply. This test results showed that only the ply which was connected to the hold-down was effective in carrying tension load. On the compression
side however, the compression forces were mostly transferred through bearing contact which resulted in uniform strains across the depth of the CLT panels.

Significant strains were observed mostly at the exterior edge of the two exterior CLT panels and there was only miniscule strain transfer across inter-panel boundary to the interior CLT panels. The extreme edges of the exterior CLT panels showed maximum strain levels, which dropped rapidly with increasing distance away from the exterior edge. The strain reduced to near zero at the interior edge of the exterior panels.

Figure 8: Strain on CLT across diaphragm (positive cycle)

Figure 9: Strain on CLT across diaphragm (negative cycle)

Figure 10: Strain on tension straps across diaphragm

Figure 11: Displacement readings in string pots 1-4

Figure 12: Displacement readings in string pots 5-8

4.3 STRING POT AND LOAD-CELL READINGS

4.3.1 Measurement of Screw Slip

Figures 11 and 12 show the variation of string pot displacements at the CLT-glulam joints which tracked the slip in the screws connecting CLT panels to glulam beams. The string pot readings for each face of the glulam (or slip plane) were averaged. Note that string pots 7 and 8 (along the free-end glulam) showed greater readings than the other string pots (at fixed support and middle glulam). This could be attributed to the fact that only the screws contributed to the shear resistance at the free-end while the tension straps and hold-down could have reduced the shear demand on the screws along the fixed-end and middle glulam beams, causing less slip.
4.3.2 Measurement of Nail Slip
Figure 13 shows the variation of string pot displacements at the panel-to-panel connections (i.e. nailed surface spline connections) which tracked the slip in the nails along the length of the surface spline. The slips at the spline connections measured by string pots 16, 17 and 18 were greater than the slips measured by string pots 13, 14, 15. This could be attributed to the fact that hold-down at the ends were stiffer than tension straps at the middle seam.

4.3.3 Hold-down force variation
Figure 14 shows the variation of hold-down force with respect to the applied force. The hold-down force readings measured by the load cells were consistent but were slightly smaller in magnitude than the applied force. In addition to hold-downs, the screws connecting CLT panels to glulam at the fixed support could have contributed to the tension resistance of the diaphragm (i.e. uplift or separation of the diaphragm from the fixed support).

4.3.4 Diagonal Distortion of Diaphragm
Figure 15 shows the variation of displacement of diagonal string pots reading with respect to the applied force at the free end. The displacement readings in string pots 20 and 21 were attributed to the overall diagonal (shear) deformation of the diaphragm. All the fastener slips during load application as well as the bending and shear deformations of the CLT panels directly contributed to the diagonal distortion (apparent shear deformation). Overall, the diaphragm displayed higher apparent shear deformation on the positive cycle which contributed to the lower stiffness of the diaphragm in positive displacement cycle as observed in Figure 7.

5 DIAPHRAGM FAILURE ANALYSIS
The test was carried out until the actuator force dropped to about 30% of the peak force for both directions (i.e. restoring force dropped to about 30% of peak force). By then, the tension straps on both side of the diaphragm had failed, causing significant drop in the force readings. Once the straps failed, the glulam underneath the central seam also split in the middle due to tension.
Figure 16 shows the variation of strain for strain gauge 33 with respect to free end force applied on the diaphragm. The strain data shows that the extreme tension strap on the tension region during negative cycle yielded at peak negative load. However, the actual rupture of the straps only occurred beyond peak load as shown in Figure 16 (also see Figure 7). Post test examination revealed that the screws and the hold-down fasteners had no sign of excessive deformation (see Figures 18 and 21). Additionally, little to no crushing of wood was observed during the test. However, at the surface splines, nails were observed to withdraw from CLT panels and once the plywood splines were detached or buckled upward (see figure 19). It was observed that the nails had undergone substantial deformation when the diaphragm was pushed beyond the peak strength (see Figure 20). Thus, evidence suggested that the combined interactive strength of nailed connection and tension straps governed the ultimate strength of the diaphragm.

Camera images and sensor data also suggest sliding and rotation of panels to be the primary energy dissipation mechanisms.

Figure 17: Go Pro footage of diaphragm test

T = 1251 s
F = -31 kip/138 kN
D = -5.9 in./150 mm

Figure 18: Relatively intact screws after the test

Figure 19: Withdrawal of spline post testing

Figure 20: Deformed nail connection after the test

Figure 21: Intact hold-down at the end of the test

Figure 22: Failure at tension strap location

6 DIAPHRAGM DEFLECTION

Table 3 shows the preliminary comparison between the NDS computed and measured values for different components of diaphragm deflection at the LRFD design load level. The values for fastener slip were obtained from section 11.3.6 of the 2018 NDS [10] and the
contribution of fastener slip to diaphragm deformation was obtained based on similar assumptions used to derive Equation B-1 for CLT shear walls in the 2021 SDPWS (row 3 of Table 3). The average of sensor reading for positive and negative cycles were utilized into equation B-1 of 2021 SDPWS to estimate the contribution of each component slip to total diaphragm deflection (row 4 of Table 3).

The calculated value of diaphragm deflection of 1.06 in. (26.9 mm) based on NDS provisions was 79% of the average measured deflection of 1.34 in. (34 mm). As bending and shear deformations \( \delta_b + \delta_s \) were not directly measured from the test, it is not shown in Table 3. The diaphragm deformations due to nailed surface spline slip \( \delta_{ls} \), CLT-to-glulam screw slip \( \delta_0 \), and uplifts in hold-downs and tension straps \( \delta_{hd} + \delta_{ts} \), were derived from measured data using the deformation mechanisms assumed in NDS. Note that the sum of the test derived deflection components shown in Table 3 is 1.49 in. (37.8 mm), which exceeded the average total deflection measured from test (1.34 in.).

It can be noted from Figure 23 that bending and shear deformations calculated from the code provisions accounted to more than 50% of the total computed diaphragm deflection. From visual observation during the test and captured video footages, the CLT panels exhibited little to no visible bending and shear deformation, which contradicted the code computed value of more than 50% contribution from bending and shear deformations. This suggests that the current deflection equation in design code may need revision.

### Table 3: Deflection values for calculated and observed data at LRFD level

<table>
<thead>
<tr>
<th>( \delta_b + \delta_s )</th>
<th>( \delta_{ls} )</th>
<th>( \delta_0 )</th>
<th>( \delta_c + \delta_{hd} )</th>
<th>( \delta_{ts} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>in. (mm)</td>
<td>in. (mm)</td>
<td>in. (mm)</td>
<td>in. (mm)</td>
<td>in. (mm)</td>
</tr>
<tr>
<td>SDPWS</td>
<td>0.55</td>
<td>0.27</td>
<td>0.18</td>
<td>0.06</td>
</tr>
<tr>
<td>Test</td>
<td>(13.9)</td>
<td>(6.8)</td>
<td>(4.6)</td>
<td>(1.5)</td>
</tr>
<tr>
<td>Test</td>
<td>N/A</td>
<td>0.48</td>
<td>0.58</td>
<td>0.43</td>
</tr>
<tr>
<td></td>
<td>(12.1)</td>
<td>(14.7)</td>
<td>(11.0)</td>
<td>(34.0)</td>
</tr>
</tbody>
</table>

*Note that the test derived deflections do not add up to the total measured deflection.

Where,
\( \delta_b \) = deflection due to bending
\( \delta_s \) = deflection due to shear
\( \delta_0 \) = deflection due to shear fastener slip (parallel to load)
\( \delta_{ls} \) = deflection due to shear fastener slip (perpendicular to load)
\( \delta_c \) = deflection due to chord slip
\( \delta_{hd} \) = deflection due to hold-down slip
\( \delta_{ts} \) = deflection of the diaphragm

Test data showed that the ply in CLT panels directly attached to hold-downs (top ply in this case) experienced substantial tension. The ply on the opposite face without a direct connection to hold-downs was not effective in carrying tension force. Hence, it is recommended that only the top ply with direction load path to hold-downs be used for tension chord design. In contract, the test showed that for the compression region, both the top and bottom CLT plies developed near equal compressive strains. Based on this observation, it is recommended that all ply parallel to the compression force direction be used for compression chord design.

A preliminary comparison between the NDS computed and measured diaphragm deflections showed that the current equation in the design code may underestimate the CLT diaphragm deflection. It appears that the code equation overestimates the bending and shear contributions to the overall CLT diaphragm deflection. Further study may be necessary to develop a revised cantilever CLT diaphragm deflection equation for design purpose.

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REFERENCES


