SOLUTIONS FOR UPPER MID-RISE AND HIGH-RISE MASS TIMBER CONSTRUCTION

FIRE PERFORMANCE OF CROSS-LAMINATED TIMBER WITH ADHESIVES CONFORMING TO 2018 EDITION OF ANSI/APA PRG-320

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Client: Natural Resources of Canada (NRCan)
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1. INTRODUCTION

Structural fire resistance and charring behaviour of cross-laminated timber (CLT) have been well documented in the past decade. In North America, FPInnovations conducted several standard fire-resistance tests with CLT assemblies conforming to the 2011 to 2017 editions of the CLT manufacturing standard ANSI/APA PRG 320 [1]. The results of these tests [2, 3, 4, 5] served development of calculation methods for determining fire resistance of CLT elements exposed to standard fire conditions [6, 7], which are now implemented into Annex B of CSA O86-14 [8] and the National Design Specification (NDS) for Wood Construction [9]. It was found from these standard fire-resistance tests that once the 1<sup>st</sup> lamination charred, the general trend is that the charring rate of the subsequent laminations increased, regardless of whether it was a floor or wall assembly. It was also found that the thickness of laminations and the performance at elevated temperatures of the adhesives played an important role in the charring behaviour of CLT. This behaviour is typically not observed for glue-laminated timber face-bonded with phenolic adhesives and resins.

While the structural fire resistance of CLT assemblies can be determined using the calculation methods referenced above, to meet code compliance, the results of compartment fire tests showed that exposed surfaces of CLT have an impact on the fire growth, intensity and duration, which was not observed in CLT compartments fully encapsulated by fire-resistance rated gypsum board [10, 11, 12, 13, 14, 15, 16]. Heat delamination of CLT laminates can produce considerable fire growth intensity at a later stage in a fire when fresh and uncharred lumber suddenly becomes exposed to fire and ignites, as opposed to continuously decreasing once the decay phase is initiated.

During the revision process of the 2012 version of ANSI/APA PRG 320, in which FPInnovations actively participated, heat delamination (fall-off) of CLT laminates was raised as an important performance issue that could have severe negative impacts on CLT construction in North America, namely for taller buildings. This specific behaviour of CLT has an impact on the effective charring rate as well as on room fire dynamics, where fall-off leads to additional contribution of the CLT elements to fire growth and intensity. Building code officials and fire chiefs, among others, expressed major concerns related to this and the need to address such behaviour in fire conditions. Among other work being overseen by the ANSI/APA PRG 320 Technical Committee to resolve these concerns, FPInnovations initiated a series of small-scale testing to specifically identify a suitable test method and/or develop new and improved methods for evaluating fire (or heat) performance of adhesives used for face bonding in CLT elements [17, 18, 19, 20]. Based on the results of these tests, it was recommended that the mandatory flame test of CSA O177 Annex A.2 [21] become mandatory in ANSI/APA PRG 320 to eliminate adhesive heat delamination characteristics in CLT.

While the small-scale test methods suggest that heat delamination characteristics can most likely be captured adequately, the ANSI/APA PRG 320 Technical Committee remains uncertain as to whether building officials and fire chiefs would deem these changes to be adequate to alleviate their concerns. Southwest Research Institute (SwRI) developed a compartment fire test to assess adhesive performance under a severe design fire scenario [22]. The test method involves a 4-hour room fire exposure of an unprotected and loaded 2.44 x 4.88 m (8’ x 16’) CLT ceiling panel. The thermal environment in the room simulates a studio apartment fire based on the fire development curve of Test 1-4 from Su et al. [13].
In the 2018 edition of ANSI/APA PRG 320, two (2) mandatory adhesive test methods have been added in an attempt to avoid heat delamination characteristics, which may result in an increased rate of charring and contribution to fire growth (Figure 1):

1. A small-scale flame test to be conducted in accordance with Annex A.2 of CSA O177 glulam manufacturing standard [21] using 8-layer CLT specimens made of 20-mm thick laminations. The test is successful if the total delamination length is 3 mm or less, when determined from digital imagery analysis over the inner 5 bond lines.

2. A full-scale compartment test, as detailed in Annex B of ANSI/APA PRG 320. An adhesive passes the test if the CLT does not delaminate during the cooling phase of the fire, and fire re-growth and secondary flashover are not observed.

![Figure 1. ANSI/APA PRG 320 (2018) adhesive elevated temperature mandatory tests](image)

In Canada, adhesives used in glulam need to conform to the full set of requirements set forth in CSA O112.9 [23] “Evaluation of Adhesives for Structural Wood Products (Exterior Exposure)” or CSA O112.7 [24] “Resorcinol and Phenol-Resorcinol Resin Adhesives for Wood (Room and Intermediate Temperature Curing)”. The bondline fire performance is to be evaluated from either the mandatory CSA O177 Annex A.2 small-scale flame test and ASTM D7247 [25] at a minimum target bondline temperature of 220°C, or from a full-scale fire-resistance test in accordance to CAN/ULC S101 [26] (which is similar to ASTM E119 [27]). Adhesives used in CLT need to conform to the full set of requirements set forth in CSA O112.10 [28] “Evaluation of Adhesives for Structural Wood Products (Limited Moisture Exposure)” and, as per the 2012 edition of ANSI/APA PRG 320, sections 2.1.3 and 3.3 of the 2008 edition of AITC 405 [29] (which refers back to ASTM D7247 at a minimum target bondline temperature of 220°C). The plywood DOC PS 1 flame test [30] is also recommended (not mandatory) to assess whether an adhesive exhibit heat delamination characteristics, which may increase CLT charring rate. Given the large variety and different adhesive requirements, Dagenais [31] and Dagenais & Ranger [32] tried to correlate these adhesive standard qualifications and the results from small-scale to large-scale fire tests. One can observe from Table 1 that adhesives meeting the requirements of either of the CSA O177 Annex A.2 flame test or the
plywood PS 1 flame test would result in furnace tests where little, if any, heat delamination would occur and would most likely result in a uniform charring rate throughout the CLT elements. However, very little fire-resistance test data is available publicly to validate the charring rate of CLT elements manufactured with adhesives that fulfill the new 2018 ANSI/APA PRG 320. The CSA O177 Annex A.2 flame test was also not conducted on specimens face-bonded with the PUR2. Moreover, the results also suggest that satisfactory CSA O177 Annex A.2 or DOC PS 1 tests would result in room/compartment fire tests where little, if any, increase in heat release rate and fire growth due to laminations falling-off would be observed.

Table 1. Previously tested adhesive fire performance vs. North American Qualifications [31, 32]

<table>
<thead>
<tr>
<th>Adhesive</th>
<th>Certification (1)</th>
<th>Test Method</th>
<th>Room Fire Test (5,6)</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>CSA O112.9</td>
<td>CSA O112.10</td>
<td>ASTM D7247</td>
</tr>
<tr>
<td>PUR-1C</td>
<td>-</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>PUR-2C</td>
<td>Yes</td>
<td>-</td>
<td>Yes</td>
</tr>
<tr>
<td>PUR2</td>
<td>Yes (4)</td>
<td>-</td>
<td>Yes (4)</td>
</tr>
<tr>
<td>EPI</td>
<td>-</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>MF1</td>
<td>Yes</td>
<td>-</td>
<td>Yes</td>
</tr>
<tr>
<td>MF2</td>
<td>Yes</td>
<td>-</td>
<td>Yes</td>
</tr>
<tr>
<td>MF3</td>
<td>Yes</td>
<td>-</td>
<td>Yes</td>
</tr>
<tr>
<td>PRF</td>
<td>Yes</td>
<td>-</td>
<td>Yes</td>
</tr>
</tbody>
</table>

(1) According to adhesive suppliers’ evaluation reports (most are publicly available).
(2) PUR-1C = 1-component PUR currently used in most/previous CLT manufacturing.
(3) PUR-2C = 2-component PUR used in glue-laminated timber.
(4) PUR2 = “improved” 1-component PUR currently under qualification to meet 2018 ANSI/APA PRG 320.
(5) Delam. = heat delamination was observed visually resulting in an increase in heat release rate.
(6) Delam. = heat delamination was observed visually and through charring data analysis.
(7) Type of MF is unknown [40], but was either MF1 or MF2.

On this matter, the USDA Forest Products Laboratory performed fire tests on CLT elements made with various types of adhesives exposed to the ASTM E119 standard time-temperature curve [40]. They found that CLT elements face-bonded with melamine-formaldehyde (MF, although the type of MF used is unknown) and phenol-resorcinol-formaldehyde (PRF) exhibited little, if any, delamination while those made with one-component polyurethane (PU1) and an emulsion polymer isocyanate (EPI) exhibited high degrees of delamination. Oregon State University [35, 36] found similar behaviour when testing CLT floor and wall elements made of various lumber species and adhesives. The CLT elements made with the PU1 adhesive exhibited heat delamination, regardless of the wood species. Those made with the MF did not show appreciable heat delamination. Brandon & Dagenais [20] conducted medium-scale furnace tests with CLT elements exposed to the fire development curve of Test 1-4 from Su et al. [13]. The study evaluated five adhesives: two one-component polyurethanes (PU1 is the traditional adhesive used in CLT and PU2 is an improved version of PU1 intended to meet North American adhesive requirements), a MF, an EPI and a PRF. Only PU1 exhibited heat...
delamination, resulting in an increased charring rate. The same 5 adhesives were further tested using the DOC PS 1 flame testing for plywood [30]. PU1 and EPI exhibited heat delamination. Lastly, standard fire-resistance tests showed that a CLT panel made with 25-mm laminations and the PU2 showed moderate heat delamination and resulted in a fairly constant charring rate of 0.66 mm/min throughout after being exposed to the ISO 834-1 [41] standard fire curve for 2 hours [37].

Based on the above, there is a need to evaluate CLT manufactured with adhesives conforming to the new 2018 ANSI/APA PRG 320 adhesive requirements and their effects on the resulting charring rate when exposed to the standard fire CAN/ULC S101 [26] and ASTM E119 [27]. Revisiting the charring rate of CLT manufacturing with non-delaminating adhesives is important for further reviewing and improving existing fire-resistance design methodologies such as Annex B of CSA O86-14 and Chapter 16 of the NDS.

2. OBJECTIVE

The objective of this research is to evaluate CLT face-bonded with adhesives that meet the new 2018 ANSI/APA PRG 320 with respect to elevated temperature requirements and their effects on the resulting charring rates when exposed to the standard time-temperature curve of CAN/ULC S101 (similar exposure to ASTM E119).

The results can ultimately be used to propose modifications to the charring models currently used in CSA O86-14 and the NDS, if found conclusive.

3. TECHNICAL TEAM

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Dedicated work and professionalism from the staff at the National Research Council of Canada Fire Research Laboratory is also acknowledged, namely Dr. Noureddine Bénichou, Patrice Leroux, Robert Berzins, Eric Gibbs, Pier-Simon Lafrance and Mark Weinfurter.

4. METHODOLOGY

Four (4) adhesives were used in this study: 1-component polyurethane (PUR1, traditional adhesive used in CLT), 1-component polyurethane (PUR2, improved version of PUR1 intended to meet North American adhesive requirements), melamine-formaldehyde (MF) and a phenolic-resorcinol-formaldehyde (PRF) (considered as the benchmark, per CSA O112.9 [23]). At the time of writing the report, PUR2 was going through the qualification process and is specifically formulated to meet the new requirements of ANSI/APA PRG-320 (2018). The
remaining two are certified for use in glulam in accordance to CSA O122 and ANSI 405 [42]. The 4 adhesives are the same as PUR-1C, PUR2, MF1 and PRF, shown in Table 1.

For both the CSA O177 Annex A.2 flame test and standard fire tests conducted in this study, the adhesives were uniformly applied using rollers on one side of the lumber boards only. The mass of each board was assessed prior to and after glue application, to ensure that sufficient adhesive was applied. The adhesive spread rate, open and close assembly times, applied pressure as well as pressing and curing times followed the adhesive suppliers’ recommendations and technical data sheets.

### 4.1 CSA O177 Annex A.2 Flame Test

CLT blocks were constructed at the FPInnovations laboratory in Quebec City (Canada) using Douglas fir lumber boards, in accordance with CSA O112.9 and CSA O177. Blocks of 138 mm wide by 458 mm long were prepared in accordance with the requirements detailed in Annex A.2 of CSA O177; using a total of 8 laminations of 20 mm in thickness (Figure 2). The lumber was free of defects and had a relative density between 0.48 and 0.57 (average of 0.52). The direction of the growth rings of the 8 laminations was oriented so that they were alternating. The CLT blocks were then cut into specimens of 150 mm wide by 160 mm high and 40 mm thick. All specimens were then conditioned at 20°C and 65% relative humidity until testing. The flame test was conducted at FPInnovations laboratory in Quebec City (QC) (Figure 1a).

![Figure 2. CLT specimens for CSA O177 Annex A.2 flame test](image)

Each specimen was exposed to the flame for 5 minutes, and then rapidly rotated 180° about the plane of burning and subjected to the flame for another 5-min period. After the test, the specimens were allowed to cool down for 10-15 minutes prior to being smoothly cut in half for digital imagery analysis. The inner five (5) bond lines were digitally measured to determine the total length of delamination on the charred surface only. As stipulated in the standard, failure in the wood, checking or open bond lines due to knots were not regarded as delamination. For a successful test with softwoods, CSA O177 requires that the sum of the delamination of the five (5) inner bond lines, of each given assembly, do not exceed 3 mm.
It is noted that in a standard CSA O177 Annex A.2 flame test, two (2) test assemblies should be prepared; one each for the maximum and minimum assembly times recommended by the adhesive supplier. In this study, because of the limited number of test assemblies, only 1 set of assembly time was evaluated using the recommended assembly time by the adhesive suppliers. We may consider more future tests to reflect the minimum and maximum times in accordance with the standard.

4.2 Charring Evaluation

A total of nine 5-plys (175 mm) CLT specimens of 914 x 914 mm (3’ x 3’) were constructed using lumber boards of the Spruce-Pine-Fir (SPF) No. 1/No. 2 grade at the FPInnovations laboratory in Quebec City. The nominal 2x6 (38 x 140 mm) lumber boards were graded in accordance with CSA O122 by a certified glulam manufacturer and planed to 35 mm in less than 24 h prior to gluing. The lumber was free of defects, conditioned at 20°C and 65% relative humidity before gluing and had a relative density between 0.34 and 0.56 (average of 0.41). Three (3) adhesives were used for the 9 CLT specimens, 3 specimens per adhesive: PUR2, MF and PRF. All lumber boards were tightly positioned to limit any gaps between them.

Fibreglass insulated thermocouples (type G/G-24-KK) were inserted throughout the CLT specimens. Three (3) thermocouples were inserted during the gluing process (Figure 3) and six (6) were inserted afterward by drilling pilot holes from the back surface (i.e., surface not exposed to fire), for a total of 9 thermocouples per CLT specimen located near their geometric centre (81 thermocouples for the whole assembly). The drilled pilot holes were sealed using Hilti FS One firestop sealant to prevent air leakage and moisture movement during the fire tests.

The 9 panels were inserted into 3 larger supporting CLT elements manufactured with PUR1 adhesive, in which 914 x 914 mm (3’ x 3’) square holes were cut to insert the specimens. A single surface plywood spline was used to fasten the supporting CLT elements together side-by-side. Self-tapping screws at 45° were used to fasten the 9 CLT specimens to the supporting CLT panels. Gaps surrounding the 9 CLT specimens were sealed using Hilti CP 660 flexible firestop foam (Figure 4). Plywood overlay was screwed on top of the whole assembly to prevent smoke leakage and/or flame-through from occurring. The 9 CLT specimens were positioned along the furnace in
such a way as to subject them to similar exposure (Figure 6). All specimens were then left to room conditions at NRCC’s fire laboratory until testing (Figure 5).

All 9 CLT specimens, including the supporting CLT panels, were exposed to the standard fire curve of CAN/ULC S101 until all thermocouples inside the specimens reached 300°C. Given that charring behaviour was the objective of this test, no load was applied to the specimens. The fire test was conducted at NRCC’s Fire Research Laboratory in Ottawa (ON).

![a) Sealing gaps using Hilti CP 660](image1)

![b) CLT specimens inserted into supporting CLT panels](image2)

**Figure 4. Mounting of CLT specimens into supporting CLT panels**

![a) View from inside furnace](image3)

![b) View from top of furnace](image4)

**Figure 5. Mounting of CLT specimens at NRCC Fire Research Laboratory**
4.3 Structural Fire Resistance

Two (2) full-size commercial CLT panels of 1,829 mm (width) x 4,877 mm (length) (6’ x 16’) were purchased from a Canadian CLT manufacturer, Structurlam Mass Timber Corporation, for conducting a full-scale standard fire-resistance test. The CLT panels were 5-plys (175 mm) in thickness face-bonded using the PUR2 adhesive. They were of the V2 layup, per ANSI/APA PRG 320, using 35-mm thick laminations. The CLT panels were fastened together side-by-side using a single surface plywood spline and 5” wood screws. Two (2) layers of 12.7 mm (½”) plywood were laid and screwed on top of the entire assembly to prevent smoke leakage and/or flame-through from occurring. Figure 7 shows the installation of the CLT specimens prior to the full-scale fire-resistance testing.

Fiberglass insulated thermocouples (type G/G-24-KK) were inserted in the CLT panels near the geometric center of the floor assembly at approximately 100 mm away from the panel-to-panel joint (Figure 8). Three (3) thermocouples were inserted by drilling pilot holes parallel to the glue lines and three (3) were inserted by drilling pilot holes from the back/top surface (i.e. surface not exposed to fire). The pilot holes were sealed using Hilti FS One firestop sealant to prevent air leakage and moisture movement during the tests.

The CLT panels were exposed to the standard fire curve of CAN/ULC S101. A superimposed load of 3.6 kPa was uniformly applied throughout the floor assembly, representing a 50% loading ratio under such test conditions (span, CLT layup, etc.). According to the current fire-resistance design method in Annex B of CSA O86-14, a one-dimensional charring rate of 0.80 mm/min should be used and would result in a time to failure of 106 min. Should the heat delamination be effectively eliminated and a one-dimensional charring rate of 0.65 mm/min be used throughout, a time to failure of 131 min is obtained (a 23.5% increase). It is important to note that using 0.80 mm/min would result in a 1.5-hr fire-resistance rating while using 0.65 mm/min would result in a 2-hr fire-resistance rating.
Figure 7. Full-scale CLT fire-resistance test at NRCC Fire Research Laboratory

Figure 8. Instrumentation of full-scale CLT specimens
5. RESULTS

5.1 CSA O177 Annex A.2 Flame Test

Table 2 provides the summary of the total length of delamination observed from digital imagery. The measurements of the lengths of delamination in the bond lines were performed using “ImageJ” freeware. The high-resolution images of the samples were calibrated using a 10 x 10 mm grid to allow for precise pixel measurements, which were then converted to millimeters. The individual lengths of delamination were measured with a 0.1 mm precision and the total length of delamination was rounded to the nearest 0.5 mm, as stipulated in Annex A.2 of CSA O177. Many of the specimens required the use of a 0.07 mm gauge to confirm the presence of delamination at the bond lines.

Figure 9 shows a closer view of the lengths of delamination observed during this study. It can be seen that PUR1 exhibited a high degree of heat delamination. PUR2 showed improvement, but failed the maximum 3.0 mm total length of delamination criterion. MF had a maximum total length of 2.0 mm, while PRF showed no delamination.

<table>
<thead>
<tr>
<th>Adhesive</th>
<th>Specimen</th>
<th>Pass / Fail</th>
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<tbody>
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<td>PUR1</td>
<td>13.5</td>
<td>Fail</td>
</tr>
<tr>
<td></td>
<td>15.0</td>
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</tr>
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<td></td>
<td>11.0</td>
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<tr>
<td></td>
<td>12.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>17.5</td>
<td></td>
</tr>
<tr>
<td>PUR2</td>
<td>3.0</td>
<td>Fail</td>
</tr>
<tr>
<td></td>
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<tr>
<td></td>
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Table 2. Total length of delamination (mm)

Interestingly, most of the specimens made with PUR2, MF and PRF showed a high degree of wood failure perpendicular to the grain. As the wood is exposed to the flame, it dries and shrinks in all 3 orthotropic directions (i.e. longitudinal shrinkage for some laminations and a mix of radial/tangential shrinkage for the others), resulting in differential stresses applied at the bond lines. The wood failure is an indication that the resistance in tension perpendicular to grain is now the weakest link in the specimens and that the bond lines maintain their integrity.
5.2 Charring Rates

The furnace test ran for 200 min, at which point most of the thermocouples within the 9 CLT specimens reached 300°C. Flaming was observed through the supporting CLT elements after 196 min, which triggered the end of the test. Figure 12 shows the furnace temperature in comparison to the standard time-temperature curve of CAN/ULC S101. The temperatures were within the tolerances indicated in the CAN/ULC S101 standard. The moisture content of the specimens was unfortunately not recorded due to a malfunction of the handheld moisture meter at the time of the test.

During the fire test, video footage allowed for observing a large area of the floor/ceiling surface inside the furnace. It was observed from the video footage that the 1st lamination of the supporting CLT elements to locally exhibit heat delamination (fall-off) at approximately 1 h 10 in to the test. The 2nd, 3rd and 4th laminations were observed to fall-off at approximately 1 h 52, 2 h 35 and 2 h 53, respectively. Given the supporting CLT elements were manufactured with laminations of 35 mm in thickness, the times to fall-off for each lamination suggest effective charring rates of 0.50, 0.83, 0.81 and 1.84 mm/min, with an overall charring rate of 0.81 mm/min over 4 laminations (140 mm ÷ 173 min). Fall-off from the 9 CLT panels was not observed from the video footage (from the areas that were visible from the camera).

After the test, the plywood overlays were removed from the CLT specimens. Charred locations were found along the 2 surface splines and along some of the gaps filled with the Hilti CP 660 flexible firestop foam. As shown in Figure 10, there were also portions of the supporting CLT that were completely burned-through (e.g., between specimens PUR2-1 and PRF-2). There was also evidence that the supporting CLT panels burned faster than the supported 9 CLT specimens, as shown in Figure 11, where its residual thickness was clearly thinner than the 9 CLT specimens. It is noted that the supporting CLT panels were manufactured using the PUR1 adhesive conforming to the 2012 edition of ANSI/APA PRG 320, which is known to exhibit heat delamination.

![Figure 10. CLT specimens after removal of the plywood overlays](image)
The charring rates of the 9 CLT specimens were determined using the time at which a thermocouple reached 300°C, divided by its location (depth) from the initial exposed surface. Table 3 summarizes the resulting charring rates. The charring rate per lamination is determined from the time difference between 2 adjacent laminations to reach 300°C, divided by the lamination thickness (35 mm). The global charring rate is taken as the time at which a thermocouple reached 300°C at a given depth, divided by its associated depth (35, 70 or 105 mm). Figure 13 to Figure 15 show the linear regression from all data points for each adhesive: PUR2, MF and PRF. The linear regressions are shown in an attempt to verify whether the charring rates are constant throughout (linear), and therefore demonstrating that heat delamination is not an issue for adhesives conforming to the performance requirements in the 2018 edition of ANSI/APA PRG 320. The slopes (representing the linear charring rate) and the coefficient of determination ($R^2$) are also given in Table 3 for comparison purposes to the other results.
Figure 12. Furnace temperature vs. CAN/ULC S101 standard temperature – Charring evaluation

<table>
<thead>
<tr>
<th>Adhesive</th>
<th>Per lamination (mm/min)</th>
<th></th>
<th></th>
<th>Global (mm/min)</th>
<th></th>
<th></th>
<th>Linear Regression</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1&lt;sup&gt;st&lt;/sup&gt;</td>
<td>2&lt;sup&gt;nd&lt;/sup&gt;</td>
<td>3&lt;sup&gt;rd&lt;/sup&gt;</td>
<td>1&lt;sup&gt;st&lt;/sup&gt;</td>
<td>2&lt;sup&gt;nd&lt;/sup&gt;</td>
<td>3&lt;sup&gt;rd&lt;/sup&gt;</td>
<td>Slope</td>
</tr>
<tr>
<td>PUR2-1</td>
<td>0.74</td>
<td>0.67</td>
<td>0.56</td>
<td>0.74</td>
<td>0.69</td>
<td>0.64</td>
<td>0.6449</td>
</tr>
<tr>
<td>PUR2-2</td>
<td>0.51</td>
<td>0.77&lt;sup&gt;(1)&lt;/sup&gt;</td>
<td>0.64</td>
<td>0.51</td>
<td>0.72&lt;sup&gt;(1)&lt;/sup&gt;</td>
<td>0.68</td>
<td></td>
</tr>
<tr>
<td>PUR2-3</td>
<td>0.65&lt;sup&gt;(1)&lt;/sup&gt;</td>
<td>0.56&lt;sup&gt;(1)&lt;/sup&gt;</td>
<td>0.71</td>
<td>0.65&lt;sup&gt;(1)&lt;/sup&gt;</td>
<td>0.60&lt;sup&gt;(1)&lt;/sup&gt;</td>
<td>0.67</td>
<td></td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>0.63</strong></td>
<td><strong>0.67</strong></td>
<td><strong>0.64</strong></td>
<td><strong>0.63</strong></td>
<td><strong>0.67</strong></td>
<td><strong>0.66</strong></td>
<td></td>
</tr>
<tr>
<td>MF-1</td>
<td>0.58</td>
<td>0.66</td>
<td>0.43</td>
<td>0.58</td>
<td>0.59</td>
<td>0.53</td>
<td>0.5803</td>
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<tr>
<td>MF-2</td>
<td>0.65</td>
<td>0.68</td>
<td>0.56</td>
<td>0.65</td>
<td>0.65</td>
<td>0.62</td>
<td></td>
</tr>
<tr>
<td>MF-3</td>
<td>0.58</td>
<td>0.60&lt;sup&gt;(1)&lt;/sup&gt;</td>
<td>0.61</td>
<td>0.58</td>
<td>0.58&lt;sup&gt;(1)&lt;/sup&gt;</td>
<td>0.57</td>
<td></td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>0.61</strong></td>
<td><strong>0.65</strong></td>
<td><strong>0.53</strong></td>
<td><strong>0.61</strong></td>
<td><strong>0.61</strong></td>
<td><strong>0.57</strong></td>
<td></td>
</tr>
<tr>
<td>PRF-1</td>
<td>0.59&lt;sup&gt;(1)&lt;/sup&gt;</td>
<td>0.52</td>
<td>0.60</td>
<td>0.59&lt;sup&gt;(1)&lt;/sup&gt;</td>
<td>0.53</td>
<td>0.63</td>
<td>0.5906</td>
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<td>0.68</td>
<td>0.63</td>
<td></td>
</tr>
<tr>
<td>PRF-3</td>
<td>0.64&lt;sup&gt;(1)&lt;/sup&gt;</td>
<td>0.52</td>
<td>0.47</td>
<td>0.64&lt;sup&gt;(1)&lt;/sup&gt;</td>
<td>0.63</td>
<td>0.56</td>
<td></td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>0.60</strong></td>
<td><strong>0.61</strong></td>
<td><strong>0.54</strong></td>
<td><strong>0.60</strong></td>
<td><strong>0.61</strong></td>
<td><strong>0.61</strong></td>
<td></td>
</tr>
</tbody>
</table>

<sup>(1)</sup> Determined using either 1 or 2 thermocouples (due to malfunctions).
Figure 13. Charring rate from CLT specimens made with PUR2 adhesive

Figure 14. Charring rate from CLT specimens made with MF adhesive
Char measurements were taken after the test at 3 locations per CLT specimens near the thermocouples using an electronic resistograph R650-SC (Figure 16). The resistograph is an easy-to-use device that drills a long needle drill bit into the wood. The drilling resistance is then recorded and interpreted to determine the remaining wood depth. By subtracting the remaining wood depth from the original wood dimension (175 mm), the resulting char depth and charring rate can be calculated. Table 4 provides the estimated char depths using the resistograph as well as the resulting charring rates. Presuming a 200 min test duration is a conservative assumption given that charring continues for a while once the test has ended. It can be observed that the calculated charring rates using the resistograph and 200 min test duration provide reasonable values when compared to that obtained from the linear regression of the thermocouples’ data (Table 3). Figure 17 shows an example of a measurement from the resistograph.
### Table 4. Char depths and charring rates from resistograph measurements (mm)

<table>
<thead>
<tr>
<th>Adhesive</th>
<th>Residual depth (mm) per specimen</th>
<th>Charring Rate (mm/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>PUR2-1</td>
<td>51</td>
<td>48</td>
</tr>
<tr>
<td>PUR2-2</td>
<td>33</td>
<td>36</td>
</tr>
<tr>
<td>PUR2-3</td>
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<td>46</td>
</tr>
<tr>
<td>MF-1</td>
<td>60</td>
<td>54</td>
</tr>
<tr>
<td>MF-2</td>
<td>43</td>
<td>56</td>
</tr>
<tr>
<td>MF-3</td>
<td>58</td>
<td>64</td>
</tr>
<tr>
<td>PRF-1</td>
<td>76</td>
<td>44</td>
</tr>
<tr>
<td>PRF-2</td>
<td>50</td>
<td>44</td>
</tr>
<tr>
<td>PRF-3</td>
<td>55</td>
<td>51</td>
</tr>
</tbody>
</table>

\(^{(1)}\) Charring rate based on a 200 min test duration and 175 mm initial thickness.

Given the large range of lumber relative density used to manufacture the 9 CLT specimens (0.34 to 0.56, with an average of 0.41), it would somehow be expected to have a large variability in the resulting charring rates. Equation (1) provides a relationship between the charring rate \(\beta\) (mm/min) of Douglas fir and its density \(\rho\) (kg/m\(^3\)) and moisture content \(w\) (in decimal) [43]. For lumber at 12% moisture content, a charring rate between 0.52 and 0.78 mm/min would be obtained (0.67 mm/min for a 0.41 average density), which is consistent with the range of values shown in Table 3 and Table 4.

\[
\beta = \frac{1}{[(0.002269 + 0.00457w)\rho + 0.331]}
\]  

\(\beta\) Charring rate based on a 200 min test duration and 175 mm initial thickness.
5.3 Structural Fire-Resistance

After the 1-h pre-loading period to 3.6 kPa, the recorded deflection at mid-span was 7.1 mm, which is consistent with the 7.8 mm deflection when calculated for these conditions using the V2 layup mechanical properties from ANSI/APA PRG 320. The latter does not consider the composite effect from the screwed plywood overlays to the CLT elements (i.e., for a bare 5-ply CLT V2 floor element). The moisture content of the specimens was 7.8%, 8.3% and 9.2% (average 8.4%), measured with a handheld moisture meter.

The test lasted for 185 min, at which time all of the thermocouples within the CLT specimen reached 300°C. No failure was, however, reached, but structural failure was imminent. From the test observations, it appeared that the screwed plywood overlays provided additional strength and stiffness to the overall assembly, thus allowing for a greater deflection without structural failure. Figure 18 shows the furnace temperature in comparison to the standard time-temperature curve of CAN/ULC S101. The temperatures were within the tolerances indicated in the CAN/ULC S101 standard.

![Furnace temperature vs. CAN/ULC S101 standard temperature – Full-scale test](image)

According to ISO 834-1 [41], deflections are to be measured at the location where maximum deflections are expected to occur, in this case at mid-span. Mid-span deflections were recorded at 3 locations, labelled DFL-04, DLF-05 and DFL-06, as shown in Figure 19 and Figure 20. ISO 834-1 defines the load-bearing capacity as the ability to support the test load determined by the amount of deflection and rate of deflection. The latter is deemed not applicable until a deflection of \( L/30 \) is reached, where \( L \) is the clear span, and is to be calculated over 1-min intervals. It is noted that these criteria are not mandatory for floor assemblies when tested in accordance to CAN/ULC S101. The maximum deflection of \( L/30 \) (153 mm) was first reached at 158.4 min (average of 159.1 min for all deflection gauges), as shown in Figure 19. The limiting rate of deflection of 13.4 mm/min was first reached at 171 min (Figure 20). The latter can therefore be assigned as the deemed failure time.
The charring rates of the full-scale fire-resistance test were determined using the same methodology described in Subsection 5.2. Table 5 summarizes the resulting charring rates from the full-scale fire-resistance test, as well
as the slopes and coefficients of determination (R²) from linear regressions of the thermocouples’ measurements (300°C isotherm). It can be observed that an average 0.57 mm/min charring rate is obtained, with a high R² value of 0.9646 (Figure 21). When using 0.57 mm/min with the calculation method of Annex B of CSA O86, a time to failure of 149 min and a mid-span deflection of 84 mm are obtained for a bare CLT element (no composite action from plywood overlays). An average deflection of 109 mm was measured at 149 min during the full-scale fire-resistance test. Furthermore, when using Equation (1) with the measured moisture content of 8.4% and a product density of 485 kg/m³, as per the CLT manufacturer [44], a charring rate of 0.61 mm/min is obtained, which is 8% higher than the average value of this full-scale fire test.

<table>
<thead>
<tr>
<th>Placement method</th>
<th>Per lamination (mm/min)</th>
<th>Global (mm/min)</th>
<th>Linear Regression</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1&lt;sup&gt;st&lt;/sup&gt;</td>
<td>2&lt;sup&gt;nd&lt;/sup&gt;</td>
<td>3&lt;sup&gt;rd&lt;/sup&gt;</td>
</tr>
<tr>
<td>Parallel</td>
<td>0.47</td>
<td>1.09</td>
<td>0.46</td>
</tr>
<tr>
<td>Perpendicular</td>
<td>0.61</td>
<td>0.47</td>
<td>0.66</td>
</tr>
<tr>
<td>Average</td>
<td>0.54</td>
<td>0.78</td>
<td>0.56</td>
</tr>
</tbody>
</table>

Table 5. Charring rates from full-scale fire-resistance test (mm/min)

![Figure 21. Charring rates from full-scale fire-resistance test (CLT with PUR2)](image)
6. DISCUSSION

6.1 Length of delamination

The current criterion of 3 mm in CSA O177 Annex A.2 has been determined on a proposed 1% delamination of the total length of the bond lines of glulam specimens [45]. For an 8-lamination specimen (40 mm wide), the inner 5 glue lines represent a total length of 200 mm (5 x 40 mm) and the 1% criterion results in 2.0 mm. However, when developing the test method for glulam members, 0.9 mm and 1.5 mm lengths of delamination were observed on 2 PRF specimens (PRF is deemed as the benchmark in terms of performance, as stipulated in CSA O112.9), representing a 0.5-0.75% delamination. As such, it was agreed to relax the requirement by increasing the criterion to 1.5%, which results in a maximum length of delamination of 3 mm. The test method and its performance requirements have since then been implemented into Canadian and American glulam standards. Since their implementation, there has been no evidence that glulam elements manufactured with adhesives fulfilling these performance requirements have exhibited heat delamination when exposed to fire.

Although the PUR2 CLT specimens failed by 0.5 mm, the results of this present study support that the current 3% criterion for face-bonding CLT elements is adequate for properly distinguishing adhesives that would be “good performers” to those that would be “poor performers” in fire conditions. In this study, only 1 specimen made with PUR2 adhesive failed the maximum length of delamination of 3 mm (Table 2). According to CSA O177, an additional series of 5 specimens would be allowed to be prepared and tested should only 1 of the 5 specimens fail to meet the maximum length of delamination requirement. However, no additional tests were conducted due to specimen limitations (not sufficient specimens left to conduct a 2nd series of tests). Conducting a 2nd series of tests with PUR2 specimens may have led to satisfactory results. Given that PRF is deemed as the benchmark in terms of performance, per CSA O112.9, and that no delamination was observed for all PRF specimens in the current and previous studies [17, 33], no further relaxation should be made to the 3 mm criterion for both glulam and CLT elements.

As indicated in Table 1, a strong correlation can be found between the various standard test methods to the actual fire performance of an adhesive. All test results referenced in Table 1 suggest that an adhesive meeting the requirements of CSA O177 Annex A.2 will result in furnace and room fire tests where little to no heat delamination would be observed. While Table 1 was lacking of supporting data with respect to this adhesive meeting the CSA O177 Annex A.2 flame test, there is evidence that furnace and room fire tests with CLT manufactured with the PUR2 adhesive have led to satisfactory results, namely with respect to no delamination (i.e., constant charring rate) and no fire re-growth during the decay phase.

While PUR2 failed by 0.5 mm from only 1 series of test, the current study suggests that this adhesive could likely be qualified for face-bonding CLT elements in accordance with the 2018 edition of ANSI/APA PRG 320. A full standard qualification is, however, required by the adhesive suppliers.

6.2 Charring behaviour

Figure 22 shows the average charring rates for all 3 types of adhesives. It can be observed that both MF and PRF specimens charred at a fairly constant rate throughout the 3 laminations, while being slightly lower than the commonly-used value of 0.65 mm/min for softwoods. A slight deviation is observed at the 2nd bond line (70 mm)
for the PUR2 adhesive, however its resulting overall charring rate, generally, agrees very-well with the commonly-accepted value of 0.65 mm/min.

The results suggest that CLT manufactured with an adhesive meeting the CSA O177 Annex A.2 flame test requirements could use the commonly-accepted one-dimensional charring rate of 0.65 mm/min during fire exposure.

![Figure 22. Average charring rate from CLT specimens](image)

### 6.3 Effect of thermocouple installation method

Recent concerns were raised with respect to the installation method of thermocouples to record the temperature profiles in a low-conductive material such as wood. Charring rates reported by previous fire-resistance tests conducted by FPInnovations and NRCC were also questioned. In a recent study conducted by Farhni et al. [46], it was suggested that only the thermocouples laid parallel to the isotherms deliver correct temperature readings (i.e., thermocouples laid parallel to the glue lines for CLT). While their results seem to suggest a better correlation between the charring rate from inlaid (parallel) thermocouples and the residual timber section after removing the charred layer, no further investigation was made to determine whether the values were “realistic” rather than “correct”. Moreover, it should be noted that temperatures beyond the charred layer (> 300°C) are irrelevant for determining charring rates and could therefore be ignored.

Furthermore, placement of thermocouples during the gluing process may be feasible for laboratory-made specimens. However, it is quasi-impossible to do such instrumentation on specimens bought directly through a manufacturers’ production line. For design purposes, the latter would provide a much more accurate representation of the actual commercial product performance in fire. Laboratory-made specimens provide very
relevant characteristics and behaviour in fire conditions for research and development purposes, but are only valid for “ideal” products (unless defects are specifically included in the process).

In 2018, Ranger et al. [47] conducted a demonstration fire of a wood-framed I-joist floor supported by a nail-laminated timber (NLT) exit shaft wall. The NLT was instrumented at various depths using fibreglass insulated thermocouples (type G/G-24-KK) installed parallel and perpendicular to the isotherms. Based on the test data, there was no evidence that the thermocouple placement method affected the temperature readings.

During this present study on charring behaviour of CLT panels manufactured with adhesives conforming to the latest 2018 adhesive requirements of ANS/APA PRG 320, all specimens were instrumented using thermocouples placed parallel and perpendicular to the isotherms. The intent was to further investigate whether their placement methods may have an impact on temperature measurements and therefore on the resulting charring rates. It was found that, based on the slope of linear regressions for 6 out of 9 small-scale specimens, the glued-in thermocouples (parallel) reached 300°C faster than those drilled perpendicular to the glue lines (Figure 23). The opposite was observed for 1 specimen (Figure 24). No difference was found between the two placement methods in two specimens (Figure 25), where they both resulted in similar slopes and coefficients of determination (R²). Furthermore, the overall charring rate over 3 laminations (105 mm) was also identical for the full-scale fire-resistance test, with a slightly higher R² value for the thermocouples inserted from the top surface (perpendicular to the isotherms), as shown in Figure 26.

Similar to the observations from the NLT exit shaft demonstration fire test [47], the results of this present study suggest that the placement of thermocouples has little to no impact on temperature measurements related to evaluating charring rates in wood elements. Caution should however be given to ensure that the pilot holes are properly drilled (depth and straightness), the tip of the thermocouples is properly placed at its intended position and the pilot holes are properly sealed to prevent localized airflow from occurring.

The results supports the fact that previously-reported charring rates from studies conducted by FPInnovations and other organizations when instrumenting wood specimens perpendicular to the isotherms, are adequate and accurate enough for design purposes.
Figure 23. Effect of placement of thermocouples (glued-in TCs faster than drilled TCs)

Figure 24. Effect of placement of thermocouples (drilled TCs faster than glued-in TCs)
Figure 25. Effect of placement of thermocouples (no difference)

Figure 26. Effect of placement of thermocouples from full-scale fire test (no difference)
7. CONCLUSION AND RECOMMENDATIONS

The objective of this research was to evaluate CLT elements face-bonded with adhesives that meet the new 2018 ANSI/APA PRG 320 with respect to elevated temperature requirements and their effects on the resulting charring rates when exposed to the standard time-temperature curve of CAN/ULC S101 (similar exposure to ASTM E119). Four (4) adhesives were used in this study: 1-component polyurethane (PUR1, traditional adhesive used in CLT), 1-component polyurethane (PUR2, improved version of PUR1 intended to meet North American adhesive requirements), melamine-formaldehyde (MF) and a phenolic-resorcinol-formaldehyde (PRF) (considered as the benchmark, per CSA O112.9).

CSA O177 Annex A.2 flame tests were first performed on CLT specimens made of Douglas fir lumber. PUR1 exhibited a high degree of heat delamination. PUR2 showed greater improvement, while failing the maximum 3.0 mm total length of delamination criterion. MF had a maximum total length of 2.0 mm, while PRF showed no delamination. Only one specimen made with PUR2 adhesive failed the maximum length of delamination criteria of 3 mm. According to CSA O177 Annex A.2, an additional series of 5 specimens would be allowed to be prepared and tested, but was not done in this study. Conducting a second series of tests with PUR2 specimens may have led to satisfactory results. Given that PRF is deemed to be the benchmark in terms of performance, per CSA O112.9, and that no delamination was observed for all PRF specimens in the current and previous studies, no further relaxation should be made to the 3 mm criterion for both glulam and CLT elements. The current 3 mm criterion for face-bonding CLT elements is adequate, yet severe enough, to properly distinguish adhesives that would be a “good performer” to those that would be a “poor performer” in fire conditions.

Moreover, nine 5-plys (175 mm) CLT specimens were constructed using Spruce-Pine-Fir (SPF) No. 1/No. 2 grade lumber to verify potential delamination during fire conditions. The 9 specimens (3 PUR2, 3 MF and 3 PRF) were supported in larger CLT panels manufactured using the PUR1 adhesive. No load was applied as the objective was to evaluate their charring behaviour when exposed to the standard fire CAN/ULC S101 (similar to ASTM E119) for 200 min. Video footage during the test showed that the supporting CLT elements exhibited localized heat delamination (fall-off). Fall-off from the 9 CLT panes was not observed from the video footage. Based on linear regressions of all data points, the average charring rates were found to be 0.65, 0.58 and 0.59 mm/min for the CLT elements face-bonded with PUR2, MF and PRF, respectively. Overall, it was observed that both MF and PRF CLT specimens charred at a fairly constant rate throughout the three laminations, while being slightly lower than the commonly-used design value of 0.65 mm/min for softwoods. A light deviation was observed at the 2nd bond line (70 mm) for the PUR2 adhesive, however, its resulting overall charring rate generally agrees very-well with the commonly-accepted value of 0.65 mm/min.

Furthermore, a full-scale fire-resistance test was conducted on a 5-ply (175 mm) CLT floor assembly of the V2 layup per ANSI/APA PRG 320. A superimposed load of 3.6 kPa was uniformly applied throughout the floor assembly, representing a 50% loading ratio. The CLT elements were exposed to the standard fire CAN/ULC S101 (similar to ASTM E119). The test lasted for 185 min, at which time all of the thermocouples within the CLT specimen reached 300°C. No failure was however reached, but structural failure was imminent. According to ISO 834-1, the limiting rate of deflection was first reached at 171 min, which is therefore the deemed failure time. Linear regression of the charring rates over three laminations (105 mm) provided an average value of 0.57 mm/min.
Recent concerns were raised with respect to the installation method of thermocouples to record temperature profiles in a low-conductive material such as wood. Charring rates reported by previous fire-resistance tests conducted by FPInnovations and NRCC were also questioned. During this present study on charring behaviour of CLT panels manufactured with adhesives conforming to the latest 2018 adhesive requirements of ANS/APA PRG 320, all specimens were instrumented using thermocouples placed parallel and perpendicular to the isotherms. The results suggest that the placement of thermocouples has little to no impact on the temperature measurements related to evaluating charring rates in wood elements. Caution should however be given to ensure that the pilot holes are properly drilled (depth and straightness), the tip of the thermocouples is properly placed at its intended position and the pilot holes are properly sealed to prevent localized airflow from occurring.

In conclusion, the results obtained in this study suggest that CLT manufactured with an adhesive meeting the CSA O177 Annex A.2 flame test requirements could use the commonly-accepted one-dimensional charring rate of 0.65 mm/min during fire exposure. A strong correlation was already found between the CSA O177 A.2 flame test and the “good” fire performance of CLT elements face-bonded with such satisfactory adhesives. This study further supports this correlation and demonstrates that the costly large-scale compartment fire test, as per Annex B in ANSI/APA PRG 320, may not be required for qualification purposes. It could, however, be suggested as an alternative qualification test method to CSA O177 Annex A.2, similar to glulam elements.

Lastly, many countries have CLT manufacturers, and not all are conforming to North American codes and standards. While the mechanical and durability performance of CLT may be suitable in each of their respective country and applicable codes and standards, the improved adhesive performance requirements in the 2018 edition of ANSI/APA PRG 320 have greatly raised the level of performance of this new generation of CLT and increased the level of difficulty for adhesive qualifications. Caution should be given to overseas CLT elements not conforming to 2018 ANSI/APA PRG 320 as it relates to their fire performance when exposed to standard fires and the fire dynamics in compartment fires.
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[38] M. Janssens, «Development of a Fire Performance Assessment Methodology for Qualifying Cross-Laminated Timber Adhesives (Draft Report - SwRI Project No. 01.23086.01.001)» SouthWest Research Institute, San Antonio (TX), 2017.


