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HEAT DELAMINATION IN CROSS LAMINATED TIMBER: INTERMEDIATE SCALE TEST BASED UPON THE NORTH AMERICAN STANDARDS

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ABSTRACT: Currently, the North American standard, ANSI/APA PRG 320: *Standard for Performance-Rated Cross-Laminated Timber*, requires a full-scale compartment fire test to qualify adhesives for use in cross laminated timber (CLT) for structural applications. This test is necessary to determine whether the adhesives will experience heat delamination - a premature adhesive failure during fire that can lead to sudden fire regrowth during the decay phase of a fire commonly referred to as a secondary flashover.

The required full-scale test is cost-prohibitive to adhesive manufacturers when developing new adhesive formulations. This paper presents work performed at the Forest Products Laboratory (FPL) focused on developing a low-cost intermediate scale test used to predict if a new adhesive formulation is likely to delaminate and, therefore, fail the full-scale PRG 320 test. In the FPL method, a 2.44 m long by 610 mm wide CLT panel is exposed to a time-temperature profile in a furnace designed to match the PRG 320 test. Additionally, the mechanical loads are scaled to target the bending moment in the PRG 320 test standard. New findings presented in this conference paper include measurements of the oxygen concentration within the furnace during the test.

KEYWORDS: fire performance of CLT, adhesives for CLT, PRG 320

1 INTRODUCTION

Cross laminated timber (CLT) is being rapidly adopted in North American buildings [1-3]. Changes to the International Building Code (IBC) have allowed increases to the height and area limits for CLT buildings [4-6]. The IBC requires that the CLT complies with the ANSI/APA PRG 320: *Standard for Performance-Rated Cross-Laminated Timber* [7] (hereafter referred to as PRG 320) which specifies test methods and minimum performance requirements for CLT panels.

One unique aspect of the PRG 320 standard that was added in the 2018 Edition is the requirement for a full-scale compartment fire test to demonstrate that the adhesive between laminations does not fail during a fire scenario.

Heat delamination, hereafter shortened to delamination, occurs when the adhesive fails as the bond line is exposed to higher temperatures prior to the char front reaching the adhesive bond line during a fire scenario. In 2017, a series of full-scale fire tests on CLT compartments was conducted. During this test series, delamination occurred in unprotected (exposed) CLT surfaces in four of the 6 tests [8-11]. Based on data from thermocouples embedded in the CLT walls, delamination occurred prior to the char front reaching the bond line. In these tests, delamination resulted in a "second flashover"; a rapid increase in temperature that occurred during the decay phase of the fire after delamination exposed fresh, uncharred wood.

Since a second flashover creates unpredictable conditions during a compartment fire, it was decided that North American CLT must not delaminate during fire scenarios [12]. A test to evaluate adhesive performance at elevated temperatures was developed and adopted as Annex B test of the PRG 320 standard. The Annex B fire test involves a full-scale, non-combustible room with a CLT ceiling in which a natural gas burner creates conditions such that the ceiling temperatures closely match those observed in early CLT compartment fires where delamination was observed [8]. An external mechanical load is applied to the CLT ceiling and an adhesive is considered to pass the Annex B test if delamination is not observed during the 4-hour test. Following the development of the Annex B test, more large-scale fire testing has been conducted with adhesives that passed the Annex B test and delamination resulting in secondary flashover was not observed[13,14].

Despite the straightforward nature of the PRG 320 Annex B test, the test method does have some drawbacks. The biggest drawback of the method is the cost. The test is costly to run because it requires a full-scale compartment

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to be constructed for each test. Furthermore, since the test geometry is different from ASTM/ISO standards, it requires laboratories to build a unique set up prior to testing. These costs have made it difficult to screen new adhesive formulations.

Previous work by the authors introduced an intermediate furnace scale test that could be used to screen new adhesives or CLT panel layouts [15]. (See Section 2 for more details on this method). The previous work evaluated CLT panels constructed with identical adhesives and layups at two scales (intermediate- and full-scale). The intermediate-scale tests had approximately 1 m^2 of exposed CLT whereas the full-scale tests conducted in accordance with PRG 320 has approximately 12 m^2 of exposed CLT [16]. In these tests, panels that delaminated at the full-scale were also observed to delaminate at the intermediate-scale. Likewise, no delamination events were observed in intermediate-scale panels that passed the full-scale test. Finally, temperatures measured within the furnace closely followed temperature profiles measured in the full-scale PRG 320 compartment fire tests.

While the previous work of Zelinka and Bourne [15] showed comparable results between the intermediate- and full-scale tests, several important questions remain regarding the utility of the method and its correlation to full-scale tests. In this paper, we examine the oxygen concentration within the furnace during the intermediate-scale tests and compare it to data collected in full scale compartment fire testing. It is part of a larger effort to develop a low-cost intermediate scale test used to predict if a new adhesive formulation is likely to fail the full-scale PRG 320 test.

2 MATERIALS AND METHODS

2.1 Materials

Several different types of CLT were tested. The adhesives used, lumber species, lumber grade, and performance in the full-scale test are included in Table 1. All specimens were 5-ply with a nominal thickness of 175 mm. The specimens were cut to 610 mm wide by 2.44 m long. Specimens were placed on top of a 1.83 m long furnace such that approximately 1.11 m^2 of mass timber was exposed to the fire in the test. Three replicates were tested for each panel configuration.

Table 1: *Panel information for the mass timber panels tested in both the intermediate and full-scale delamination test.*

Adhesive[1]	Species/grade[2]	Pass full-scale test?
MF	Douglas fir/larch V1	Y
PUR-1	SPF/E1	N
PUR-2	SPF/E1	Y
PUR-3	SPF/V2	Y

[1] MF= melamine formaldehyde, PUR=polyurethane

[2] SPF=spruce, pine, fir species group. Grades E1 and V2 are defined in the PRG 320 standard [7].

2.2 Specimen Instrumentation

Thermocouples were installed in most of the specimens to monitor the thermal profile during the exposure. From the fire-exposed side of the specimen, thermocouples were typically installed halfway through the first ply, at the first bond line, halfway through the second ply, and at the third bond line. Similar arrays were located near the center of the specimen and on each side approximately 0.61 m from the center.

Because many of the CLT specimens were commercially produced, installation of thermocouples during layup was not possible, so they were installed through 2.4-mm-diameter holes drilled from the unexposed side of the CLT. These thermocouples were made in-house from 30-gauge type K thermocouple wire (Omega Engineering GG-K-30-SLE) with welded junctions.

2.3 Panel mechanical loading

According to PRG 320 Annex B, section B9, 'The superimposed load on the CLT floor-ceiling slab shall result in 25% of the effective Allowable Stress Design (ASD) reference flatwise bending moment.' To achieve this, a scenario with two symmetrical and equal load points 0.813 m apart was implemented. For that loading scenario, the maximum bending moment occurs at the point of application of each load and the maximum shear stress is equal to the load at each actuator. With the end supports located just outside the furnace the clear span is 2.34 m with a heated length of 0.99 m. The overall specimen length of 2.44 m allows for a bearing area beyond the contact point.

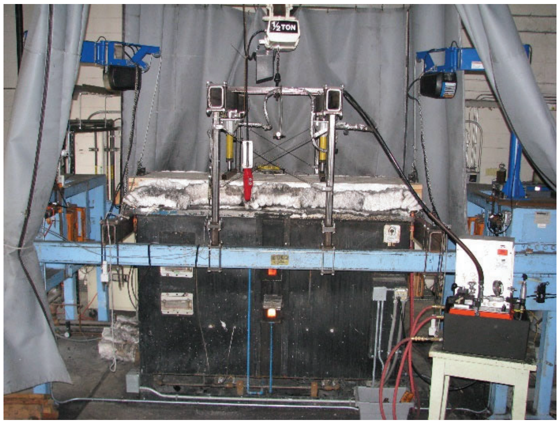

Figure 1: *Photograph of a panel being tested with the Forest Products Laboratory (FPL) intermediate-scale test method. The panel is loaded on a test frame built around a furnace. Two hydraulic actuators apply a mechanical load to match the bending moment prescribed in the standard.*

2.4 Thermal profile

An intermediate scale furnace located at FPL was used to conduct the experiments (Figure 1). The furnace is a metal box lined with ceramic fiber batting and has interior dimensions of 1.83 m long, 1.09 m wide and 1.27 m high.

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Eight diffusion flame burners are located on the floor of the furnace and the top of the furnace is open to accommodate a variety of specimen and lid configurations. Suspended 102 mm below the bottom of the specimen face are 3 thermocouples made from 20-gauge type K thermocouple wire (Omega Engineering GG-K-20-SLE). The thermocouples are insulated with ceramic beads with the junction left exposed. These thermocouples approximate the measurement taken by the 5 ceiling thermocouples in the full scale PRG-320 test. Additional furnace details can be found in [13].

In the PRG 320 fire test, a calibration to determine the fuel flow rate necessary to achieve a specified hot gas layer temperature in the compartment is conducted prior to the qualification test. The calibration is run using a diffusion burner in the test compartment and the CLT ceiling is covered with 3-layers of gypsum wall board to create an essentially non-combustible room. While recording the gas flow rate, the burner is used to achieve an average ceiling temperature that matches the ceiling temperature profile measured in the 2017 compartment fire test series where delamination occurred. Upon completion of this 4-hour calibration run, the gypsum wallboard is removed to expose the CLT ceiling and the qualification test is conducted by running the diffusion burner with the same gas flow rate as the calibration run.

The thermal profile for the FPL intermediate scale test method was created using the same approach as the full-scale PRG fire test. First, for the calibration run, a non-combustible lid was placed on the furnace and was controlled so that the thermocouple temperatures within the furnace matched the temperature profile within the PRG 320 standard. Subsequent tests, with CLT samples were run by controlling the gas flow to match the gas consumed in the non-combustible control test. Figure 2 compares the temperatures measured in the intermediate scale furnace against the specified temperatures in the PRG-320 standard.

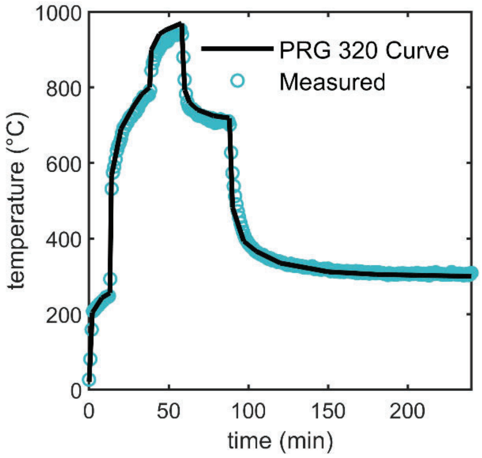

Figure 2: PRG 320 specified temperature profile plotted against the measured temperature within the furnace with an inert lid.

2.5 Oxygen measurements

To learn how oxygen concentrations may be affecting combustion within the furnace, measurements were taken in two locations: the exhaust duct and at 100 mm below the centre of the CLT specimen, location A and B in Figure 3, respectively. It is cost-prohibitive to sample multiple points simultaneously, so samples were taken in repeated experiments.

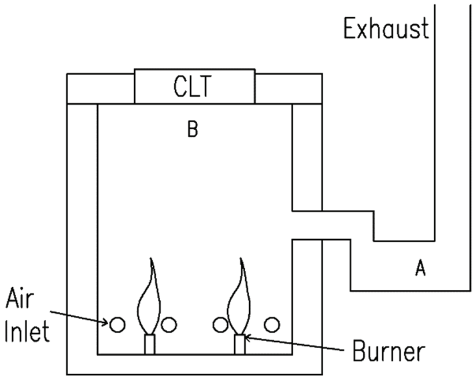

***Figure 3:** Schematic of cross section of furnace showing oxygen sample location in exhaust stream (A) and 100 mm below CLT sample (B).*

A sample is continuously drawn from the sample point, either below the CLT specimen or in the exhaust stream. The sample is then passed through a glass wool pre-filter, a heat exchanger, a filter and a drier (Sable Systems ND2 Gas Sample Drier) before being measured. Oxygen measurements were made using a paramagnetic oxygen analyser (Sable Systems PA-10). A pump is located downstream of the oxygen analyser driving the flow. The flow rate is less than 200 ml/min, which is not expected to have significant effect on the temperature or flow inside the furnace.

3 RESULTS

3.1 Temperature Results

Figure 4 shows how the temperature within the furnace during each test compares against the full-scale PRG 320 test results. In Figure 4, the full-scale results are plotted as a blue line, and the intermediate-scale results are shown as a dashed grey line. Three replicates were tested for each adhesive type; all three replicates are plotted as separate grey dashed lines. The solid black curve is the time-temperature curve from the calibration with no-exposed CLT. The figure illustrates the increase in temperature in the furnace due to the fuel contribution from the exposed CLT.

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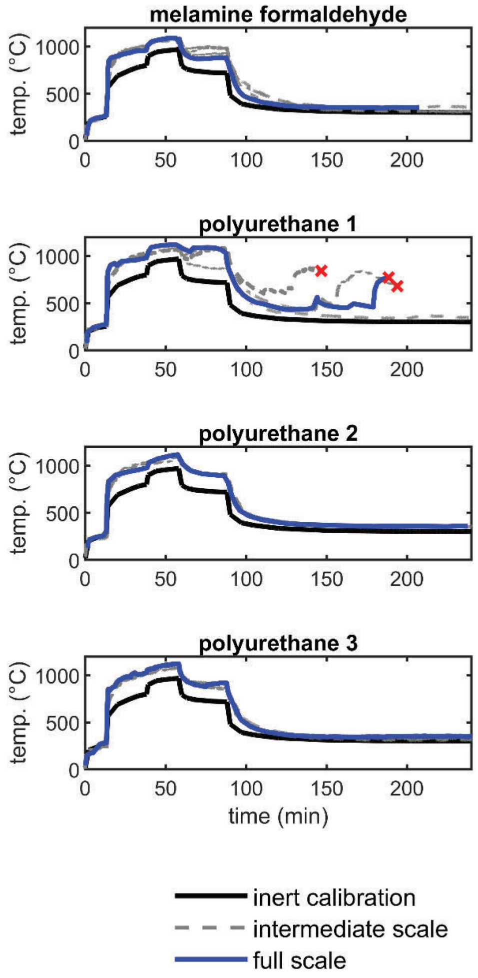

__Figure 4:__ Comparison of the furnace/compartment ceiling temperatures in the full-scale PRG 320 testing (blue) and intermediate scale test (dashed grey line). The black curve represents the temperature curve with no exposed CLT. The red "x" represents a test terminated due to failure.

Delamination was observed for the panels constructed with PUR-1 in both the intermediate- and full-scale tests. In these tests, the temperature exhibits an increase during the final phase of the test when the furnace/compartment is cooling. Further evidence of delamination was visually observed from the camera pointed at the furnace floor (Figure 5). For the panels with PUR-1, a significant amount of charred wood material was observed on the furnace floor at 90 and 120 minutes when compared to the other panels types. The furnace tests on CLT with PUR-1 were terminated before the full 240-minute limit to avoid flame through the CLT panel that could cause damage to the loading actuators.

Good correlation was observed between the intermediate- and full-scale temperature results, especially for the panels made with PUR-2 and PUR-3. In two of the three panels with PUR-1 tested at the intermediate-scale, delamination occurred which caused a rapid rise in temperature between 120 and 200 minutes. In the third replicate, the temperature in the furnace increased after 200 minutes, but did was not a full delamination event.

The correlation between the intermediate- and full-scale tests can be most easily seen in Figure 6, which plots the residual of the temperature between the intermediate- and full-scale tests. The data show that the furnace temperature was very close to the compartment temperature for the panels made with PUR-2 and PUR-3. However, for the MF panels, the temperature in the furnace test was higher than in the compartment which was most prominent between 50-120 minutes.

3.2 Oxygen Results

Initial oxygen measurements were taken with inert insulation blocks in place of the CLT specimen. The reduction of oxygen, illustrated in Figure 7, compared to atmospheric levels corresponds to the amount of gas being consumed by the burners. In both measurement locations the lowest concentration is measured during the high temperature portion of the curve between 48 and 58 minutes. It is during this portion of the test that the biggest difference between the measurement locations is observed as well. In location A in the exhaust, the oxygen concentration went as low as 10.5%. At location B near the center of the exposed specimen surface the oxygen concentration was briefly observed to go below 1%. The oxygen concentration curves between each location are very similar before 15 minutes into the test and again after 58 minutes.

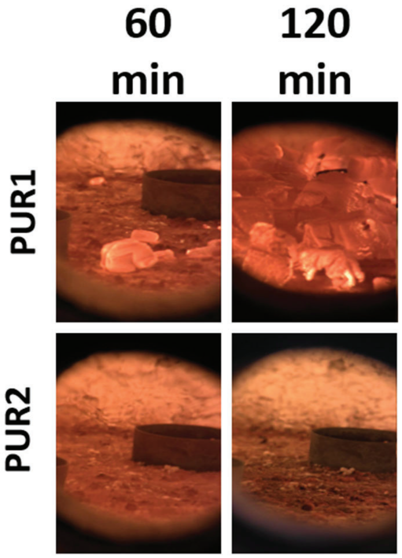

Figure 5: *Images of the furnace floor at 60 and 120 minutes into the test for polyurethane 1 (PUR1) and polyurethane 2 (PUR2).*

The low oxygen concentrations measured in the furnace are expected. Brandon and Dagenais [17] reported that it is important to match the oxygen concentrations within a furnace and compartment when developing a furnace test. They reported that in the 2017 compartment fire tests where delamination was observed, the oxygen concentration was nearly zero during the peak heat release period of the test and worked to mimic that in their furnace test by limiting the oxygen concentration between 15-80 minutes of their 180 minute test [8,17].

This data suggests that there may be adequate oxygen supply in the furnace to support combustion of wood specimens in all but the hottest portions of the test. Furthermore, it shows that there is a large difference in oxygen concentration throughout the furnace. It is measured quite low near the sample surface, the exhaust measurement is essentially an average, so the concentration must be higher somewhere else in the furnace.

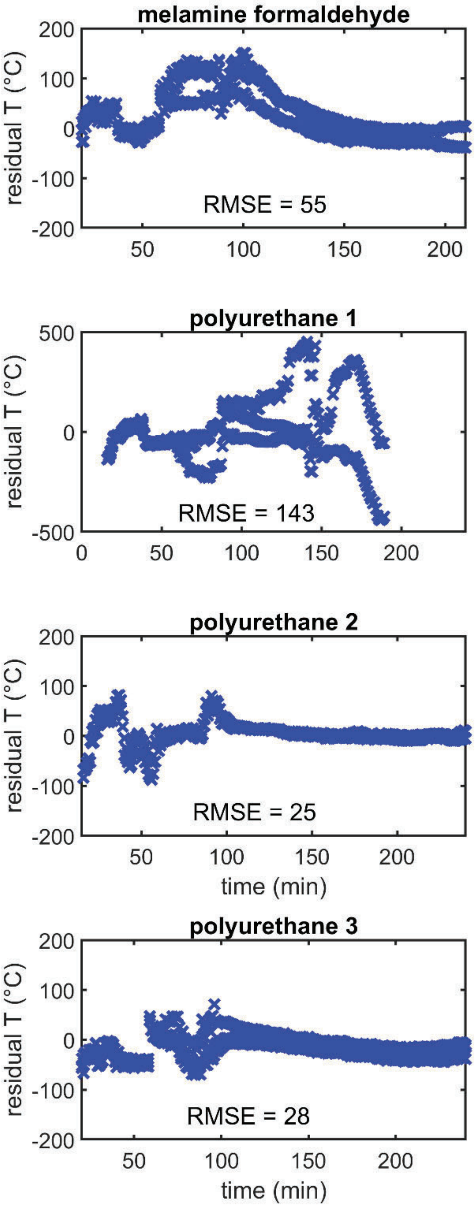

Figure 6: Plots of the temperature residuals calculated by subtracting the *full-scale* test temperature from the intermediate scale test temperature. RMSE = root mean square error calculated from the entirety of the test.

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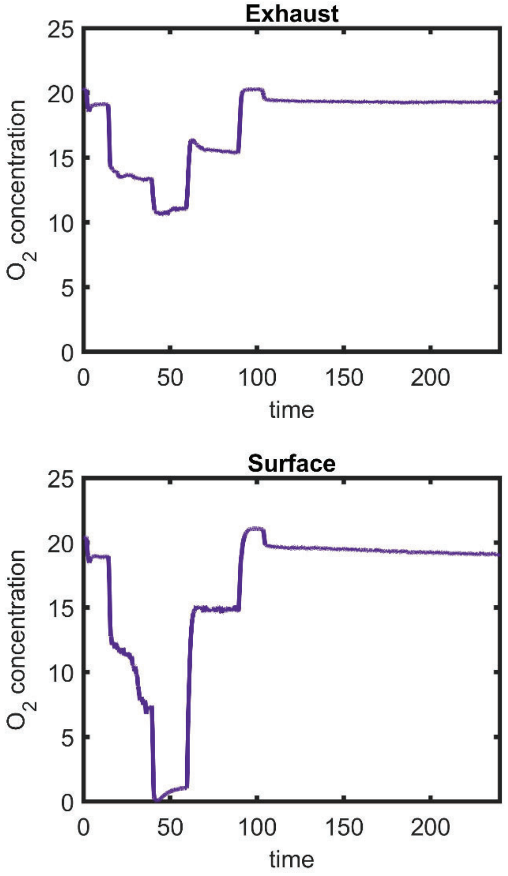

Figure 7: *Comparison of oxygen concentration in exhaust (labelled "Exhaust") versus 100 mm below specimen (labelled "Surface") when experiment is run with inert specimen in place of CLT specimen.*

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It is useful to compare the oxygen concentrations measured in this experiment to previous work where oxygen concentrations were measured in furnace tests. Schmid et al. [18] also examined the oxygen concentrations within a furnace during the testing of a CLT panel, although with a standard fire curve [19] rather than the PRG 320 fire curve. Schmid et al. also noted differences between the concentration of oxygen near the panel surface (which was near zero) and the exhaust of the furnace, which was found to vary between 5 and 10% [18]. Future work (See Section 4) will examine how these measured oxygen concentrations change when a wood panel is exposed to the PRG 320 time-temperature curve and how delamination affects the oxygen concentration both near the panel surface and in the furnace exhaust.

4 FUTURE WORK

In the future we intend to repeat the oxygen measurements with CLT specimens made with two different adhesives; one that we have previously observed to delaminate and one that has not. We will then be able to observe what effect the presence of a wood specimen has on the oxygen environment as well as the effect delamination has on the oxygen concentration.

5 CONCLUSIONS

This research aims to develop an intermediate scale test method that can be used to predict adhesive delamination under fire scenarios. The results demonstrate a good correlation between measured furnace temperatures and temperature measured near the ceiling in the full-scale PRG 320 tests that have been conducted.

Additionally, panels made with adhesives that passed the full-scale test also passed the intermediate scale test. Panels made with adhesives that failed the full-scale tests also failed in the intermediate-scale test with the exception of one replicate.

Oxygen measurements taken during the intermediate scale test show very low oxygen concentrations near the burning CLT specimen, which is similar to the oxygen concentrations measured in full-scale CLT compartment fire tests.

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