Intermediate-Scale Laboratory Method to Qualify Heat-Delaminating Adhesives for Use in Cross-Laminated Timber

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Abstract

The goal of this research was to develop a simple laboratory test for examining heat delamination in cross-laminated timber (CLT) panels. The laboratory test was designed to mimic the fire tests described in Annex B of the ANSI/APA PRG-320 standard, which is required for CLT product qualification in North America. The Annex B test requires a full-sized room (2.4 by 4.9 by 2.7 m) to be constructed and exposed to a design fire scenario. In this article, we scaled the mechanical and fire loads so that they could be conducted in an intermediate-scale furnace with 1.1 m^2 of exposed CLT panels. The mechanical loads were scaled to match the bending moment prescribed in the standard. The fire loads were scaled by matching the temperature profiles when an inert furnace lid was run and then matching the gas flow on all subsequent tests. Panels made from adhesives that passed the Annex B test passed the laboratory-scale test; panels that failed the Annex B test failed the laboratory test with the exception of one replicate. Correlations were found not only for CLT but also for a veneer-based mass timber panel. Measured temperature profiles within the furnace were similar to those measured near the compartment ceiling in the Annex B test. The scaled-down test in this article can be used to screen which adhesives are likely to pass the full-scale Annex B test.

The adoption of mass timber in North America has opened up many new avenues for wood construction. Mass timber is a general class of engineered wood where wood and adhesive are combined to form massive beams, columns, or panels, such as glue-laminated timber, structural composite lumber, or cross-laminated timber (CLT) (Jakes et al. 2016). CLT is a panel product made of alternating layers of dimension lumber and is commonly five layers (175 mm) thick and can be made up to 18 m long (Mohammad et al. 2012). The CLT panels can easily be incorporated as wall or floor systems in multistory buildings.

When wood products are exposed to fire, they char. Char provides an insulating layer that helps to protect the underlying wood substrate. Char has been recognized in the building codes since at least the 13th century (Fitz-Thedmar 1274, Knowles and Pitt 1972), and it is generally accepted that the char front progresses at a rate of 0.6 mm min^{-1} (Dietenberger et al. 2021). Although CLT can be thought of as a massive wood panel, each lamination is held together with adhesive. In early fire tests on CLT compartments, the CLT experienced *heat delamination*, where the adhesive failed before the char front reached the adhesive bondline. When heat delamination occurs in a compartment fire, this adds additional fuel to the fire; uncharred wood is now on the compartment floor, and a fresh surface is exposed on the CLT panel. This addition of uncharred wood to the fire can result in a *second flashover*, where the heat release suddenly increases and temperatures in the compartment return to their peak.

It should be noted that there is a difference between char falloff and heat delamination. Char falloff occurs when the CLT panel drops previously charred material into the compartment. While this reduces the heat insulation that char provides, no fresh surfaces are exposed, nor does the temperature in the compartment rise. In contrast, heat delamination is an adhesive failure below the char temperature of wood that can lead to a second flashover.

In 2021, the International Building Code (IBC) increased the height and area restrictions for wood buildings; CLT buildings built according to the prescriptive building codes can be 18 stories high (Anonymous 2021). The building code adoption of tall wood buildings in the United States

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followed several large-scale compartment fire tests and standardization regarding heat delaminating adhesives.

Second flashovers occurred in some of the earliest large-scale CLT compartment fire tests performed in the United States. These tests, performed at the request of the Fire Protection Research Foundation (FPRF), were conducted to better understand the contribution of CLT to compartment fire dynamics (Su et al. 2018). They tested two different opening factors and several configurations of gypsum wallboard protection, including a fully exposed CLT ceiling or wall. They observed heat delamination leading to secondary flashovers when an entire wall or ceiling was directly exposed to the environment without gypsum wallboard.

As part of the North American code acceptance process for CLT, it was determined that CLT must not delaminate in fire scenarios. The ANSI/APA PRG 320 product standard (hereafter shortened to PRG 320) specifies minimum performance criteria for CLT used in North America and was updated with additional tests to examine whether the adhesives experience heat delamination (Anonymous 2018).

The PRG-320 Annex B test for heat delamination was heavily influenced by the FPRF fire tests. The Annex B test involves exposing a compartment with a fully exposed CLT ceiling to fire. The compartment size (2.4 by 4.9 m) is roughly half the size of that used in the FPRF test; however, the opening in the compartment (51 by 1,905 mm) was scaled such that the opening factor was approximately equivalent to the smaller opening factor in the FPRF test.

In contrast to the FPRF tests where furniture was used to fuel the fire exposure to the CLT, the temperature profile for the Annex B test is controlled by a gas burner. The ceiling temperatures specified in the standard closely mimic the ceiling temperatures in the FPRF compartments test.

Annex B tests are calibrated against a test run with a completely noncombustible ceiling material. The gas burner is controlled to match the temperature of five thermocouples near the noncombustible ceiling while the gas flow is recorded. In subsequent tests, the burner is controlled to match the same gas flow in the noncombustible control. A comparison of ceiling temperatures allows the contribution of CLT to the fire to be determined.

The Annex B test screens adhesives for heat delamination and a secondary flashover that may occur in a realistic compartment fire. Therefore, failure is determined by an increase in temperature during the ''decay phase'' of the simulated compartment fire. Specifically, the temperature may not increase above 510°C between 150 minutes into the test and the test termination at 240 minutes (4 hours).

In 2017, the American Wood Council and other partners organized testing of different adhesive systems according to Annex B in support of the 2021 IBC changes (Janssens 2017). Three adhesives systems were tested: a melamine formaldehyde adhesive and two different polyurethane adhesives. One of the three panels tested was made with the same polyurethane adhesive and wood species and by the same manufacturer as those tested in the FPRF test. This adhesive also experienced delamination and fire regrowth in the PRG-320 Annex B testing. The other two adhesives passed the PRG-320 test.

The PRG 320 Annex B test is clearly related to the desired qualities of CLT under fire. Panel performance is matched to full-scale compartment fires where delamination and fire regrowth were observed in early tests. However, this test is extremely costly to run and represents a major barrier to the commercialization of new adhesives. These shortcomings have motivated research on small- and intermediate-scale tests to determine adhesive performance under fire.

Over the past decade, several researchers have examined methods for evaluating adhesive performance in CLT exposed to fire at various scales. Zelinka et al. have examined the performance of a single lap shear specimen under elevated temperatures (Zelinka et al. 2019, Miyamoto et al. 2021). They observed that all adhesives lost strength at higher temperatures and that the adhesive that failed the PRG-320 test had the lowest strength at 260°C. In further work, they applied a constant load equivalent to the shear load on the first bondline in the PRG-320 standard to small specimens and slowly increased the temperature to match measured bondline temperatures in the PRG-320 test (Zelinka et al. 2020). They observed that some polyurethane adhesives failed before the end of the simulated PRG-320 test. While these small tests appear to have promise as a potential screening tool for different formulations, more data are needed to understand how these results relate to full-scale tests. It should be noted that the PRG-320 also contains a small-scale test where a burner is applied directly to the glue lines in a CLT and the amount of delamination is examined.

On a slightly larger scale, Čolić (2021) used a radiant panel to apply a heat flux of 50 kW m^{-2} to a cross-laminated panel with a shear stress applied across a bondline. Čolić observed four different failure modes: heat delamination, char falloff, localized failure, and a mechanical failure. Delamination was observed in only 7 of the 30 panels tested, making it difficult to draw conclusive results about whether the test method can successfully screen adhesives for delamination. Others have placed an intermediate-scale CLT panel (area 0.8 m^2) in a horizontal furnace and measured the mass loss of the panel (Klippel et al. 2018, Fahrni and Frangi 2021) after (and in some cases during) the test. A large mass loss can indicate that delamination has occurred in the test. It should be noted, however, that the standard fire curve used in these tests may not represent a realistic fire exposure for the CLT panels.

Currently, there is a need for a cost-effective way to screen CLT adhesives for potential heat delamination and fire regrowth. In this study, we present one such method to measure heat delamination on an intermediate-scale furnace. The method is strongly based on the PRG-320 (and therefore the FPRF compartment fire tests). The test uses the same fire loading scenario as PRG-320, and the mechanical loads on the panel are scaled appropriately for the panel size. Delamination events can be detected from observations of the furnace floor during the test and by measuring the temperature in the furnace (which is controlled by the gas flow to the furnace). Strong correlations were observed between the full-scale test and this intermediate-scale test.

Materials and Methods

Materials

Five-ply CLT samples (nominally 175 mm thick) were cut to 0.61 m wide by 2.44 m long. Five different panels were tested: four using dimension lumber and one using veneers. Specimens were placed on a furnace with an opening of 1.83 m; approximately 1.11 m^2 of mass timber were exposed to the fire in the test.

The adhesives used and the grades of the panels are presented in Table 1. All five panels used an adhesive and panel layup configuration that were tested in a full-scale PRG-320 Annex B test. The details from three of these panels are publicly available (Janssens 2017); data on the other two panels were shared by the manufacturers.

Thermocouples were installed in most of the specimens to measure the temperatures throughout the depth. 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 approximately 0.61 m from the center as shown in Figure 1. The location of the thermocouples in the horizontal plane was shifted slightly as needed to avoid knots and board edges. Because many of the CLT specimens were commercially produced, installation of the 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.

Furnace and loading apparatus

The testing used an intermediate-scale horizontal furnace with internal dimensions of 0.99 m wide by 1.83 m long by 1.27 m tall (Fig. 2). Heating is provided by eight diffusion flame natural gas burners located in the floor of the furnace with combustion air supplied through 17 tubes, each 75 mm in diameter. Nine of the tubes are distributed through the floor of the furnace, and four more are in each end wall of the furnace, just above the floor. An exhaust port is approximately in the middle of one of the large walls and is connected to a chimney. The amount of airflow into the furnace and resulting oxygen concentration within the furnace could not be controlled. While the amount of oxygen within the furnace has been highlighted as an important parameter when comparing compartment fire and furnace tests (Brandon and Dagenais 2018), no data exist on the oxygen concentration within the compartments during the PRG-320 test.

The top edge of the furnace is a water-cooled tube, and there are two approximately ~50-mm^2 glass view ports in the wall opposite the exhaust. Suspended 102 mm below the bottom of the specimen face are three thermocouples made from 20-gauge type K thermocouple wire (Omega Engineering GG-K-20-SLE). The thermocouple leads are protected with ceramic insulators with the junction left exposed. These thermocouples approximate the measurement taken by the five ceiling thermocouples in the full-scale PRG-320 test. Because the furnace opening is 0.99 m wide and the specimen is only 0.61 m wide, 150-mm-thick blocks of insulation were placed next to the specimen to cover the remaining furnace opening. Surrounding the furnace is a structural steel frame that can be configured to load specimens in various scenarios. Part of this frame extends above the furnace to allow for specimens to be loaded in bending by two hydraulic actuators. The actuators (Enerpac RC1010) have 250-mm stroke and have a tilt saddle installed on the plunger end to help prevent side load from misalignment. The actuators are powered by an electric hydraulic pump (OTC Power Team QP60) or, for loads under 18 kN, an air-powered hydraulic pump (Enerpac WAP15008D).

The frame above the furnace is easily removable to facilitate installing and removing specimens. With the end supports located just outside the furnace, the clear span is 2.34 m with a heated length of 1.83 m. The overall specimen length is 2.44 m to allow for a bearing area beyond the contact point. The distance between the load actuators is 0.813 m; this dimension, combined with the clear span, leaves 0.762 m between each load and the closest support. The ends of the specimen are supported by rollers made of 60-mm steel pipe. A 50-mm^2 by 6-mm wall steel tube is placed under each actuator to distribute the load across the width of the specimen.

Table 1.—Panel information for the five different mass timber products tested.

	Species	Laminating board widths[a] (mm)	Grade	Pass full-scale test?
Melamine formaldehyde	Douglas fir/ larch	135	V1	✓
Polyurethane 1	SPF[b]	82	E1	
Polyurethane 2	SPF	82	E1	✓
Polyurethane 3	SPF	130	V2	✓
Veneer mass timber product	Douglas fir	610	2.1E3100 DF	✓

[a] Board widths estimated from photographs of the test specimens.
[b] SPF = spruce, pine, and fir.

Load calculation

According to PRG-320 Annex B, section B9, ‘‘The superimposed load on the CLT floor-ceiling slab shall result in 25% of the effective ASD [allowable stress design] reference flatwise bending moment.’’ A method of loading is not specified, but an approximately evenly distributed load made up of concrete blocks or containers of water or sand are typically used in full-scale tests and closely resembles real-world conditions. However, the large amount of weight required for dead loads on this short span and the material handling equipment available in our lab made loading with hydraulic actuators more practical. A scenario with two symmetrical and equal load points 0.813 m apart was chosen. 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.

The maximum effective ASD reference flatwise bending moment is tabulated for common CLT layups in table A2 of PRG-320, listed as $(F_bS)_{eff,f,0}$ in units of pound-force feet per foot of width. For layups not listed in table A2, the maximum effective ASD reference flatwise bending moment can be calculated using the shear analogy model as described in PRG-320 and chapter 3 of the Canadian CLT Handbook (Popovski et al. 2019).

Gas flow calibration and experimental procedure

The calibration method for the full-scale PRG-320 test, section B10, requires that the gas flow rates for a five-step

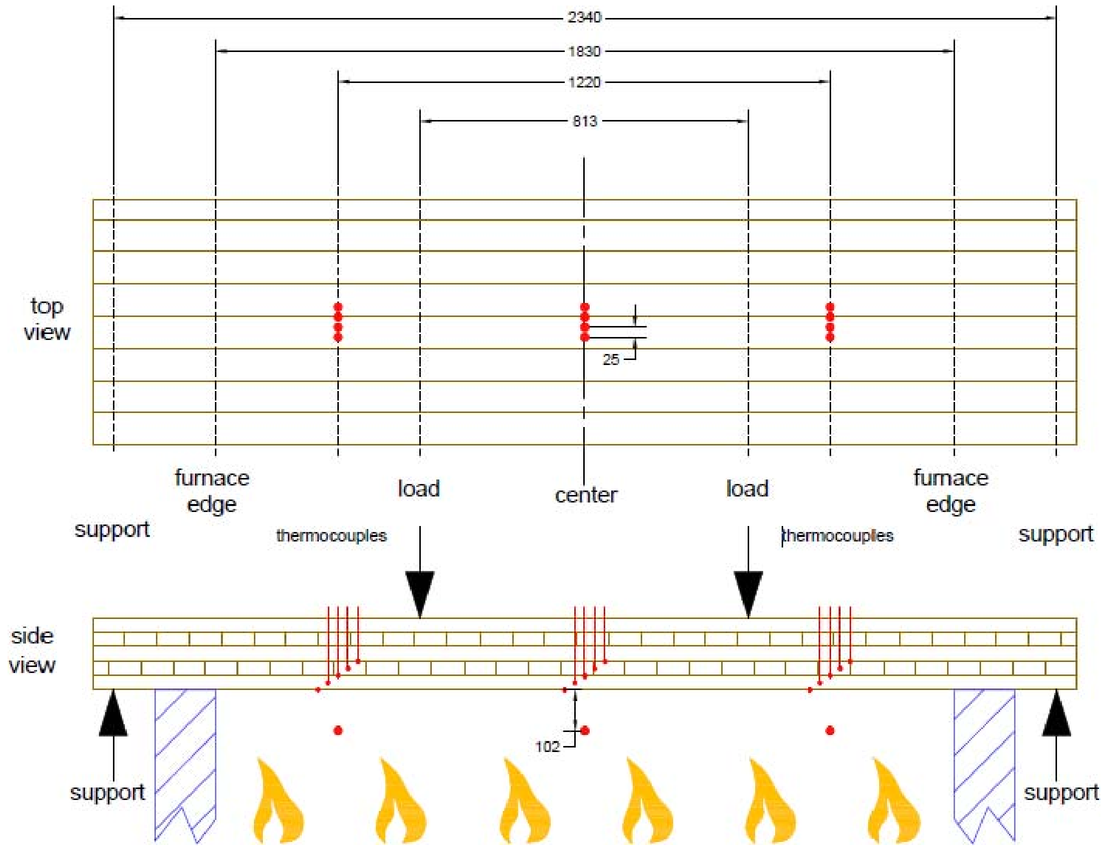

Figure 1.—Panel layup and thermocouple locations (distances given in millimeters).

profile be found to achieve specified temperatures at 13, 38, 58, and 88 minutes. Since the thermal mass of the furnace used is so much smaller than that of the full-scale room, it was found that the furnace could reach equilibrium at each step much faster, leading to a higher exposure. Therefore, the calibration procedure was changed to more accurately reproduce the conditions in the full-scale test.

Table B1 in PRG-320 gives reference time and temperature combinations as well as the required target temperatures. With noncombustible ceramic fiber blocks in

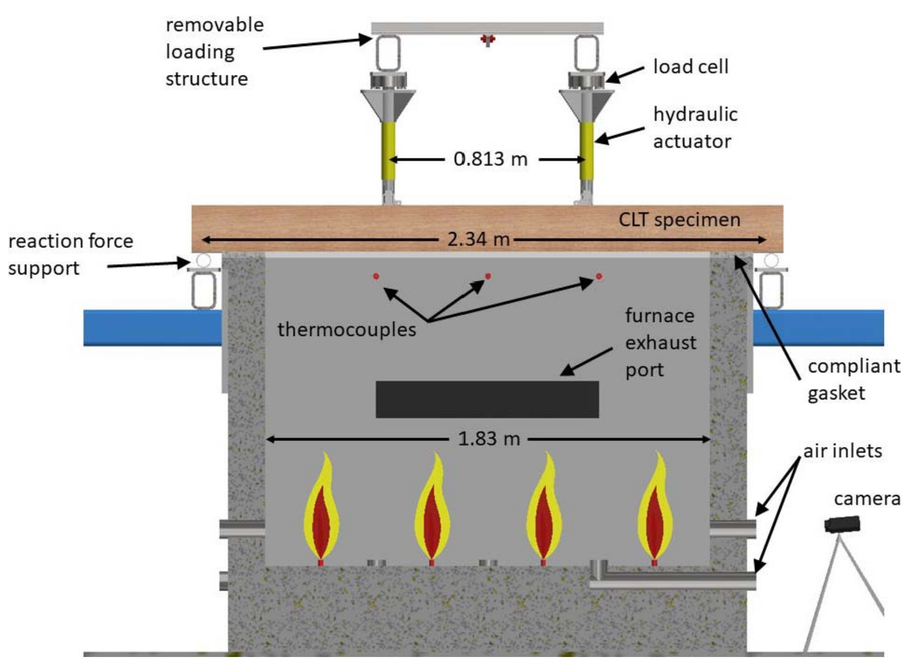

Figure 2.—Rendering of the furnace and loading apparatus used in the laboratory test.

place of the CLT specimen, the temperature profile from Table B1 was run in the furnace. It should be noted that the PRG-320 standard calls for three layers of type X gypsum wallboard covering the CLT specimen for the baseline test rather than ceramic fiber blocks. It is expected that the energy added by the gypsum board amounts to less than 1 percent of the total energy applied, and its absence should make the exposure to the specimen only slightly more severe. During the test, the gas flow rate was monitored and recorded. The furnace controller was then switched to follow a mass flow rate curve rather than temperature, and another test was run with the noncombustible ceramic fiber blocks in place of the CLT specimen and while following the gas flow rate profile. The resulting temperature profile closely matched the profile specified in table B1 of PRG-320 and is shown in Figure 3. All subsequent tests were performed with the furnace programmed to follow the gas profile attained with this procedure.

Panels were tested by applying 25 percent of the effective ASD reference flatwise bending moment with the two actuators while controlling the gas flow rate into the furnace to the same curve measured during the inert panel test. The tests continued for 4 hours or until it was deemed unsafe to continue the test due to excessive deformations that caused flames to escape between the panel and the insulative batting. The applied force was measured using load cells located between each actuator and the load frame. The displacement of the specimen was measured using string potentiometers with 300 mm of travel. The displacement was measured at the center of the specimen. Because the support beam and load frame are not perfectly rigid, their displacements were also measured so that the net displacement of the specimen center could be calculated.

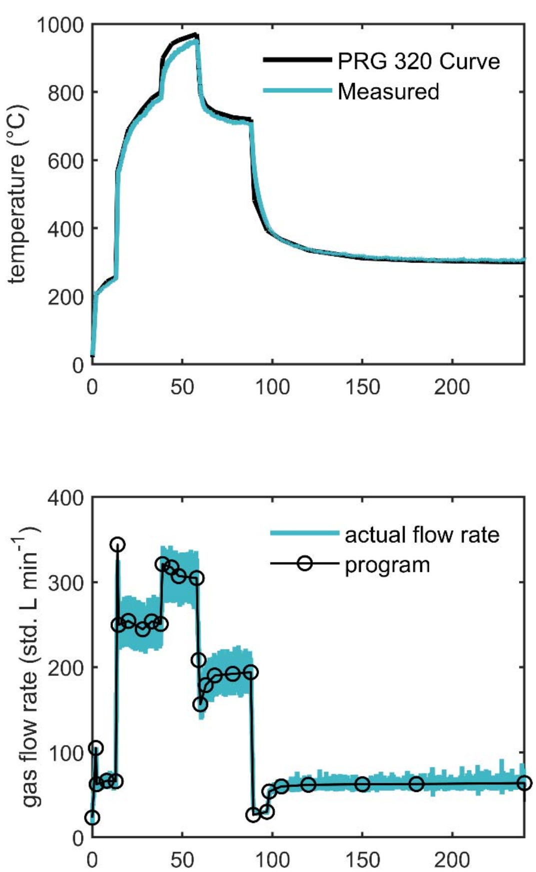

Figure 3.—Gas flow rates used in the furnace and the resulting temperature curve of an inert environment compared against the temperature profile of the inert environment specified in the PRG-320 Annex B test.

A digital camcorder was used to monitor the floor of the furnace for delamination events. The camera was positioned near the end of the furnace with a view of part of the floor through one of the furnace air inlets. Char landing on the floor was recorded, and the sound of large falls or of the specimen cracking could be recorded with the built-in microphone.

Following the test, the load frame was removed with a crane, and the panel could be removed from the furnace within 5 minutes. Panels were extinguished on removal from the furnace, and photographs were taken to examine the charred pattern and observe which layers were intact on removal.

Results and Discussion

Time–temperature curves for the four adhesives tested are plotted in Figure 4 for both the full-scale PRG-320 tests (bold blue line) and our intermediate-scale furnace tests (thin gray lines). Figure 4 also includes the time–temperature curve from the calibration run with entirely noncombustible materials (bold black line). When the temperature curves are combined with images of the furnace floor (Fig. 5), the events within the curves in Figure 4 can be interpreted in terms of delamination and char falloff events.

Excellent correlation was observed between the full-scale and intermediate-scale tests for all replicates of polyurethane 2, polyurethane 3, and the veneer-based mass timber product. For all three of these panel types, the temperatures during the decay phase after 88 minutes were very similar between the full-scale and intermediate-scale tests. Furthermore, panels made with polyurethane 2 and polyurethane 3 had strong correlation even during the heating phases before 88 minutes. For these three groups, no char accumulation was observed on the furnace floor, and it appears that no major char falloff or delamination events occurred during the test.

Further insights into how well the intermediate-scale test matched the behavior of the full-scale test can be seen in Figure 6, which plots the difference between the intermediate-scale and full-scale tests for each of the replicates along with the root mean square error (RMSE) for each of the different adhesive types. It should be noted that the measured temperatures depend on the heat release from the CLT panels in the tests, and this heat release may not scale perfectly such that a 1:1 correlation may not be expected.

When examining the different adhesives tested, the polyurethane 2 and polyurethane 3 adhesives had the lowest RMSE. Polyurethane 1 had the highest RMSE, although this measure may be misleading, as each of the three replicates had very unique trajectories to failure. Some trends can be noticed in the residuals across all panel types. The intermediate-scale test seems to be more intense, with higher temperatures seen near the 100-minute mark, and the full-scale test appears to exhibit faster cooling than the furnace test.

The temperature curves are also very similar between Annex B and two of the three intermediate-scale replicates of polyurethane 1. In those tests, there is a sharp decrease and rebound in temperature near 60 minutes. This

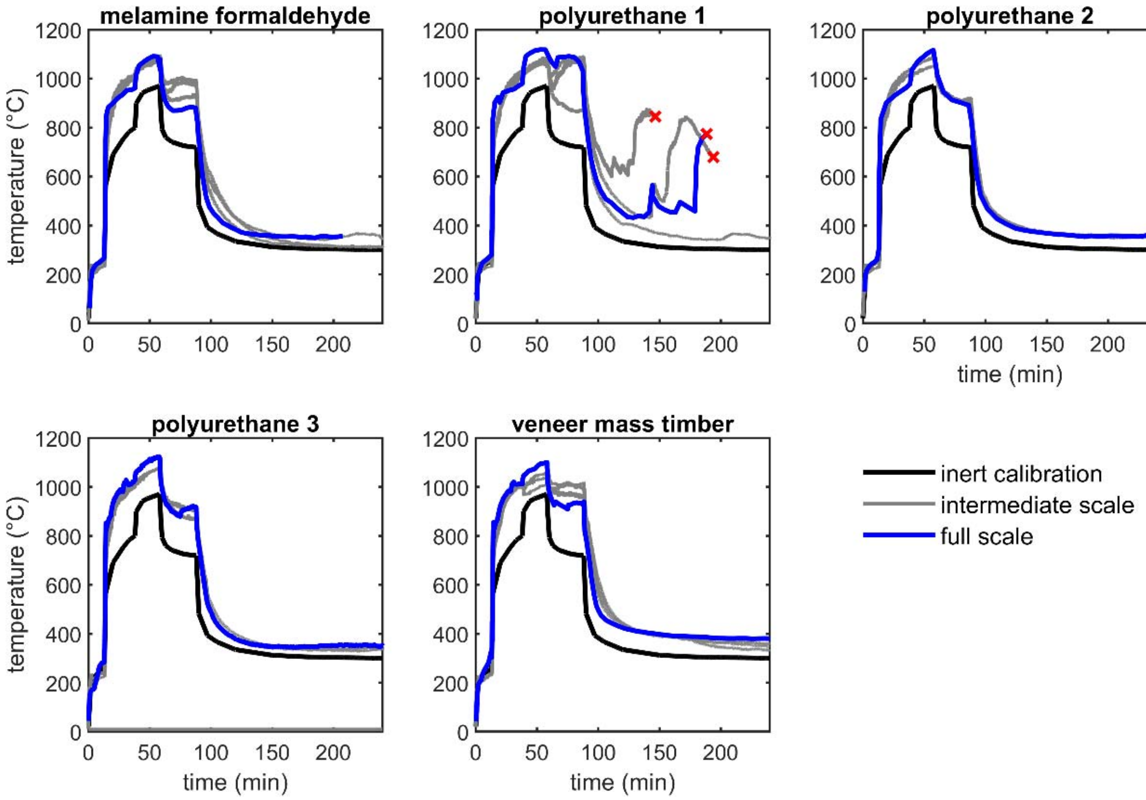

Figure 4.—Time–temperature curves for the four adhesives tested. The black curve represents the behavior of an inert environment. The bright blue line represents measured ceiling temperatures for the full-scale tests. Gray curves are the results of our intermediate-scale test.

temperature fluctuation is more pronounced in the furnace tests and corresponds with a char falloff or delamination event. We attribute the sudden decrease in temperature to air mixing within the compartment or furnace during the delamination, and this delamination event can be confirmed by the increase in debris on the furnace floor (Fig. 5). Unlike polyurethane 2 and polyurethane 3, the temperature remains above 1,000°C until the gas flow is reduced at 88 minutes. Polyurethane 1 exhibits a slower decrease in temperature (compared to polyurethane 2 and polyurethane 3). In two of the three replicates, the temperature increases as the second layer is dropped between 120 and 200 minutes. It should be noted that one replicate of polyurethane 1 did not exhibit the char falloff or delamination event near 60 minutes. This panel experienced a decay in temperature until after 200 minutes, when the temperature slightly increased, assumedly from a char falloff or delamination event. However, since the temperature in the furnace was much cooler at that point in the test, this change did not greatly affect the temperature in the compartment.

The melamine formaldehyde system exhibited different behavior on the intermediate-scale test than the full-scale compartment test. The temperature in the furnace did not decay as fast as it did in the full-scale PRG 320 test, when the gas flow was reduced at 58 minutes. As a result, they had a higher temperature during the decay phase. These higher temperatures were accompanied by the accumulation of char on the furnace floor throughout the test (Fig. 5). One replicate experienced a slight temperature increase after 200 minutes from a delamination event. However, the temperature rise was well within the acceptable range of temperatures to pass the PRG-320 test.

It is unclear why the temperature curves were so different for the melamine formaldehyde system in the intermediate-scale and full-scale tests. The panel did not exhibit a delamination event leading to a second flashover. However, char accumulation on the furnace floor and high temperatures imply that more wood was being consumed by the fire during the tests. While it is not clear what caused this enhanced combustion of wood, it could be because of differences in the panels tested at the full and intermediate scales. For example, it could be that the panels tested at the intermediate scale had larger gaps between the boards or another difference in the panel layup. While we cannot fully explain these difference in the charring behavior of the panels, importantly, the end result was the same for both the small and the intermediate test. In other words, both tests suggest that the melamine formaldehyde adhesive should pass as a non–heat delaminating adhesive.

Embedded thermocouples

Further information about the adhesive performance can be obtained by examining the bondline temperatures as a function of time. Thermocouple readings at the first bondline are presented in Figure 7 for all four adhesives tested. The char temperature (300°C) is reached between 48 and 73 minutes for all panels regardless of adhesive. The time for the first bondline to reach 300°C is presented in Figure 8.

The results of Figure 8 show that differences between adhesives that pass and do not pass the PRG-320 test are not readily apparent by examining the first bondline. While

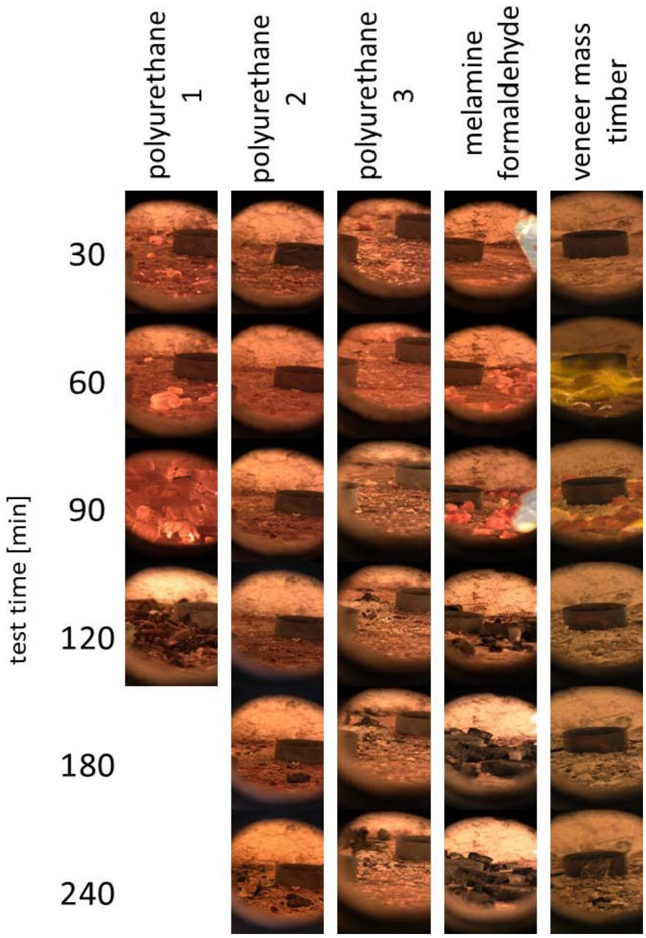

Figure 5.—Images of the furnace floor during the test showing that charred wood dropped from the specimen during the test from a representative sample.

polyurethane 1 was the only adhesive to fail the intermediate-scale test, it was the last panel to have the char reach the first bondline. However, this difference was statistically significant ($P < 0.05$) only when compared to the melamine formaldehyde adhesive, which exhibited the shortest time to char at the first bondline. The remaining two polyurethane formulations, which passed the test, showed no significant differences between either the melamine formaldehyde adhesive or the polyurethane 1 formulation.

For all panels, the char front reached the first bondline shortly after the peak heat release rate of the furnace or burner at 58 minutes. No heat delamination or early failure can be observed from the thermocouple data. However, visual observations (Fig. 5) and furnace temperature curves (Fig. 4) show that polyurethane 1 exhibited delamination of its bottom layer between 58 and 80 minutes. While it appears from the thermocouple data in Figure 7 that the bondline was over the char temperature when this occurred, the falloff event observed in polyurethane 1 appeared to have a large impact on the panel behavior throughout the remainder of the test.

Figure 9 illustrates the thermocouple behavior at the second bondline for the four adhesive systems examined. Similarly to Figure 7, the range of measured thermocouple data is plotted as a shaded range. Both the melamine formaldehyde and the polyurethane 3 group contained a replicate that had a thermocouple that was much hotter than all other measured temperatures. This outlier is plotted as a solid line for these cases. Two replicates of polyurethane 1 exhibited delamination events; since such disparate behavior was observed across replicates for polyurethane 1, each thermocouple location is plotted individually in Figure 9. Note that the replicate that did not exhibit delamination had only one thermocouple at each bondline inserted at the center of the panel.

Similar behavior can be observed in Figure 9 across the melamine formaldehyde, polyurethane 2, and polyurethane 3 groups. In these specimens, the temperature begins to increase shortly after 50 minutes and exhibits a sharp rise in temperature until approximately 100 minutes, at which point the bondline temperature continues to increase but at a much slower rate. The change in the slope of the temperature increase around 100 minutes corresponds with the decrease in gas flow to the burner at 88 minutes in the PRG-320 standard. Of these three adhesive groups, the bondline temperature increased the most for the panels made with melamine formaldehyde adhesive.

In contrast to the other panels, panels made with polyurethane 1 exhibited delamination events in all panels, but a steep temperature rise associated with failure in the ANSI/APA PRG-320 standard was observed in only two replicates. The third replicate, which had only one thermocouple placed at the center of the panel, exhibited a slight furnace temperature increase after 200 minutes, suggesting that a small delamination event may have occurred near one of the panel edges (Fig. 4). For the two replicates where a delamination occurred, a sharp temperature increase occurred between 58 and 80 minutes. During this period of the test, delamination events could be observed from the fluctuations in furnace temperature (Fig. 4) and observations of the furnace floor (Fig. 5). Because these surfaces were exposed early in the test when the temperatures within the furnace were at their hottest, the bondline temperatures increased rapidly as the char front moved quickly through the second lamination until the char temperature was reached.

While the bondline thermocouple temperatures can be useful in understanding the bondline behavior throughout the test, it should be noted that the measured temperatures may be influenced by the thermocouple installation method. Fahrni and Frangi (2021) have shown that more accurate temperature readings can be obtained if the thermocouples are installed parallel to the bondline during panel fabrication. However, such panels can be made only under special conditions, and panels made in the factory under realistic conditions cannot be tested with this thermocouple configuration. The thermocouple installation chosen for this article allowed for production panels to be tested and compared against similar panels tested at the full scale. While there may be some uncertainties in the absolute value of the temperatures recorded, a lot of understanding of the panel behavior can be gained through the embedded temperature-versus-time curves presented in Figures 7 and 9.

Utility of the intermediate-scale test

Overall, the intermediate-scale test was strongly indicative of whether a panel could pass the full-scale PRG-320 Annex B test. Panels that passed the full-scale test also passed the intermediate-scale test without fire regrowth. Furthermore, for most of the panels tested, the temperatures within the furnace closely matched the ceiling temperatures within the PRG-320 test.

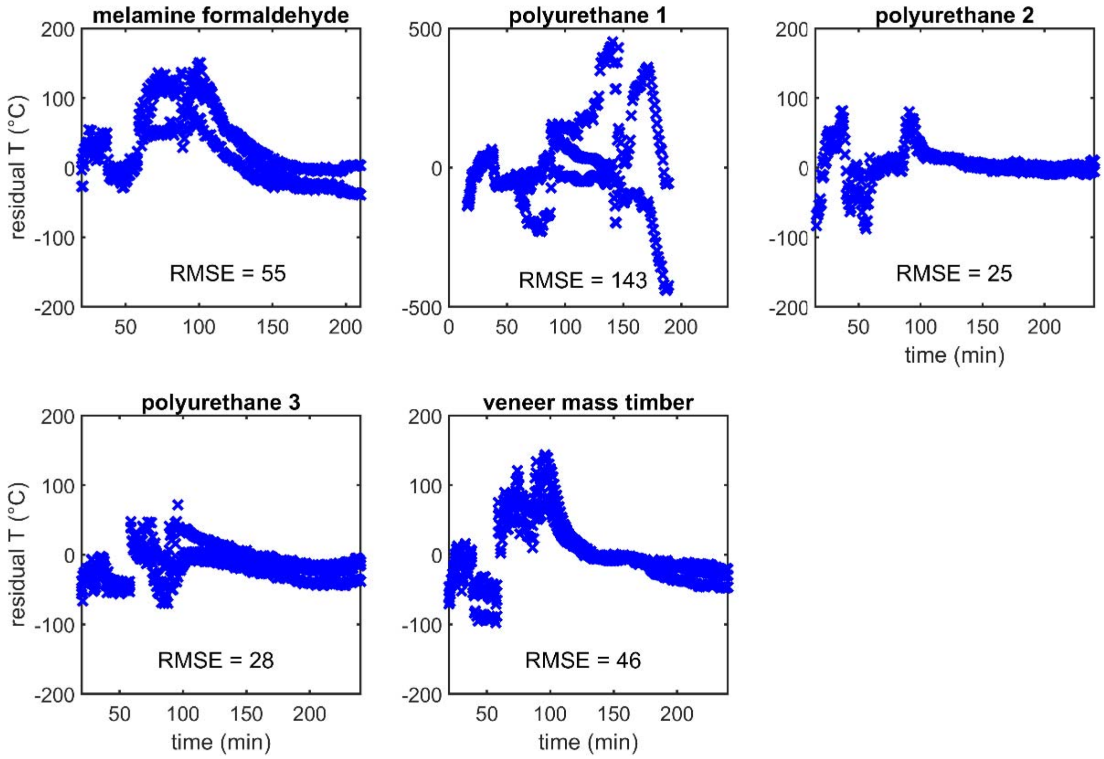

Figure 6.—Temperature residuals (intermediate test – full-scale test data) along with the root mean square error (RMSE; units degrees Celsius) for the different panels tested.

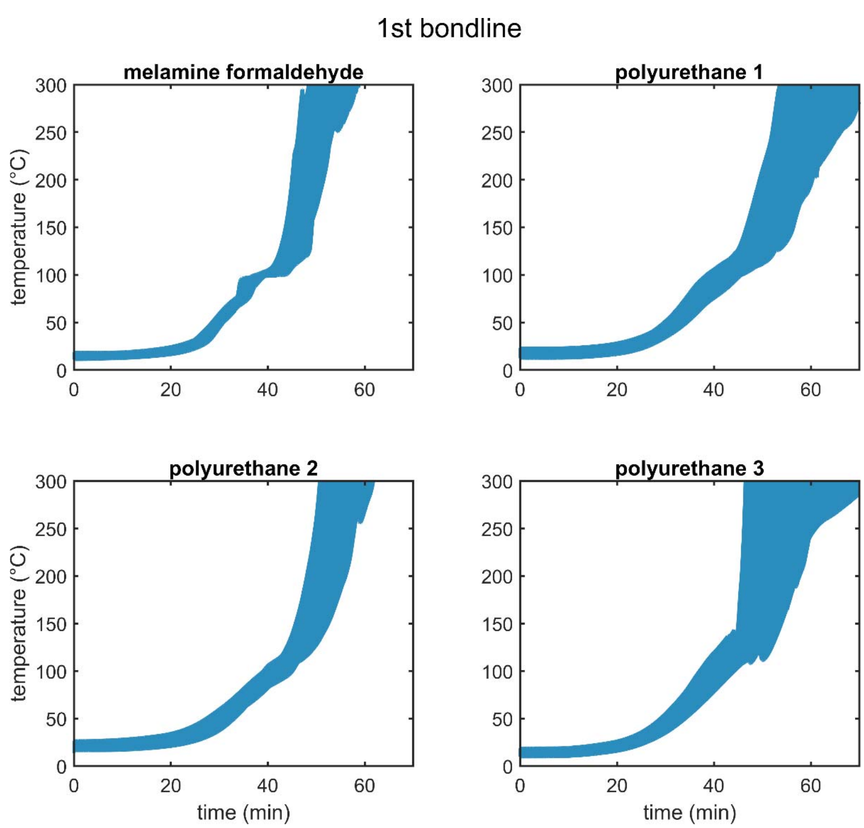

Figure 7.—Thermocouple temperatures at the first bondline as a function of time. The shaded regions represent the range of measured behaviors across the three replicates for each panel.

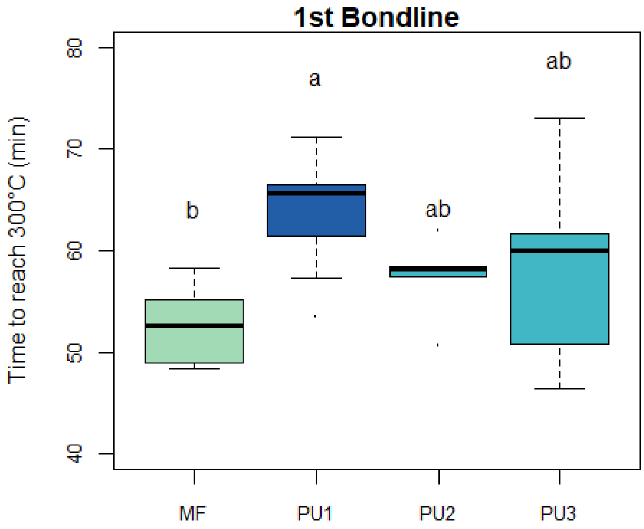

Figure 8.—Box plot showing the median time to reach 300°C at the first bondline across the four different adhesives tested (MF = melamine formaldehyde; PU = polyurethane). Letters represent sample groups from a Tukey honest significant difference test.

Despite the good correlation in many tests, there were some unexpected results. One panel from the polyurethane 1 group passed the intermediate-scale test. While the temperature and failure times in two of the three replicates matched the full-scale test, one panel did not exhibit a dramatic second flashover event and was able to endure the entire 240-minute test. In contrast, the other replicates were greatly influenced by the delamination near the 60-minute mark of the test. Further testing and modifications to the test may be needed to ensure that behavior on the intermediate scale can predict full-scale behavior.

Finally, the temperature profiles in the melamine formaldehyde replicates did not match the temperature profiles on the full-scale test. Despite higher temperatures observed at the intermediate scale during the decay phases, it appeared that these differences were not the result of a delamination event. None of the panels exhibited a sudden increase in temperature that led to a failure according to the Annex B criteria, although a slight temperature increase was observed near the end of the 240-minute test for one of the replicates.

It is unclear why only the melamine formaldehyde panels charred differently than their full-scale counterparts. Unfortunately, a further investigation into differences between the panels cannot be completed since the testing was destructive. It should be noted that in some cases, panels tested in this study were produced several years after the Annex B tests were conducted. It could be that these differences were a result of a manufacturing variable outside of panel adhesive and grade. Further controlled matched experiments may help better elucidate why slight differences in behavior were exhibited by the panels made with melamine formaldehyde adhesives in this study.

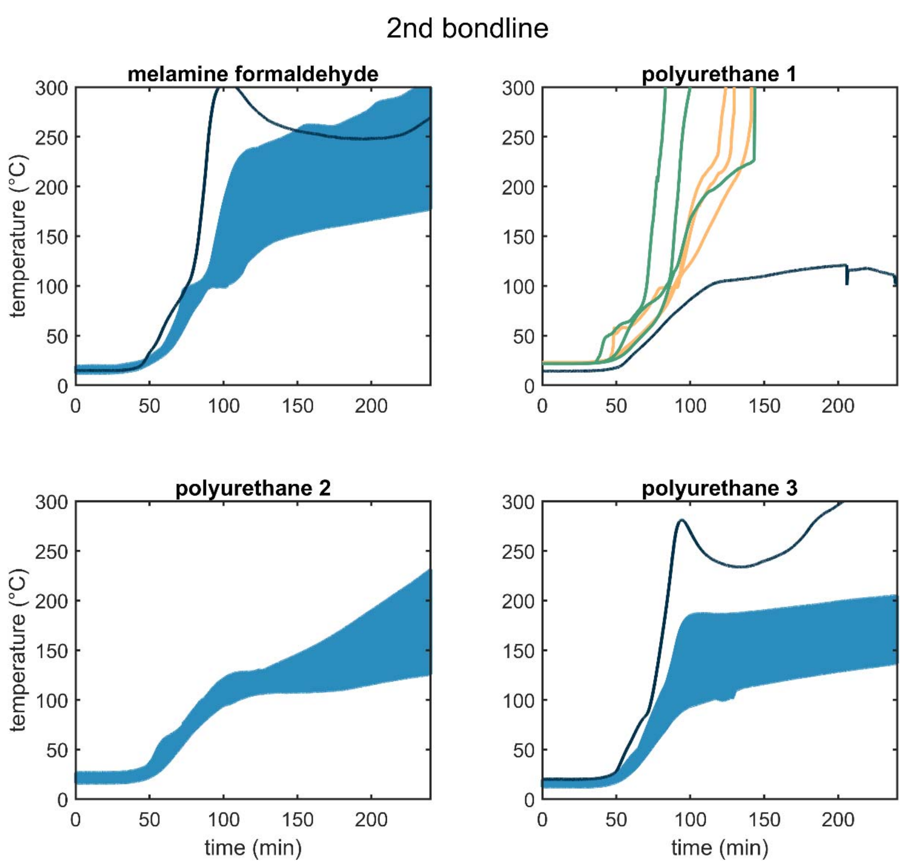

Figure 9.—Thermocouple temperatures at the second bondline as a function of time. The shaded regions represent the range of measured behaviors across the three replicates for each panel. Solid lines in melamine formaldehyde and polyurethane 3 are from a single location that exhibited a much steeper temperature increase.

Conclusions

The goal of this research was to develop a more economical method to screen different adhesive formulations for heat delamination than the full-scale PRG-320 Annex B test. To accomplish this, we applied the same fire load to smaller panels that were loaded to match the bending moment in the full-scale test.

The intermediate test method presented herein was able to closely match the compartment temperature profile of the full-scale test for CLT for most of the different panel types.

Panels made with adhesives that passed the full-scale test also passed the intermediate-scale test. For adhesives that failed the full-scale test, similar failures were observed in two of the three replicates tested.

The intermediate-scale test behavior matched the full-scale behavior not only for CLT but for veneer-based mass timber panels as well. As such, it appears that the test method can be used as a valuable screening tool to understand whether a mass timber product may delaminate in a compartment fire.

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