Small Scale Test to Measure the Strength of Adhesives at Elevated Temperatures for Use in Evaluating Adhesives for Cross Laminated Timber (CLT)

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Abstract. Cross laminated timber (CLT) is becoming widely available in North America. The product standard for North American CLT, PRG-320, has strict requirements on adhesive performance under fire scenarios. To become an adhesive certified under PRG-320, a full sized CLT compartment must be built and tested without a second flashover occurring caused by delamination. Currently, only three adhesive formulations are PRG-320 certified. This large scale test is expensive to run and only yields "pass-fail" results. In this paper we present small-scale adhesive tests performed at the Forest Products Laboratory. The tests examine a single lap shear joint. The samples are tested at elevated temperatures in a universal testing machine with an environmental chamber built around the grips. The strains are measured using digital image correlation. Tests were conducted in two different manners. In the first test, thermal equilibrium was achieved and the sample was loaded to failure. In the second test, a constant load was applied and a thermal ramp was applied until failure occurs and the temperature at failure was recorded. Importantly, the tests were compared against control samples of solid wood (no adhesive) so that adhesive strength could be normalized to that of solid wood. It is hoped that this small-scale test can aid in the understanding of CLT adhesive performance and be used to screen adhesives prior to investment in large scale adhesive qualification tests.

Keywords: Mass timber · Adhesives · Elevated temperatures · Strength · Polyurethane · Creep

1 Introduction

Mass timber buildings are being adopted worldwide with the increased use of cross laminated timber (CLT) [1]. CLT is a massive engineered wood panel made from alternating layers of dimension lumber that can be easily erected as wall or floor assemblies [2]. As with any combustible construction material, the fire performance of CLT needs to be tested and validated for use in construction.

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PRG 320 is the product standard for CLT in North America [3]. As part of the PRG 320 standard, CLT must pass fire tests that measure the adhesive performance under a fire scenario. In early fire tests on CLT compartments funded by the Fire Protection Research Foundation (FPRF), fire regrowth, also called a second flashover, occurred [4]. The fire regrowth occurred when a ply from a CLT panel delaminated before the char front had reached the bondline and the compartment temperatures were still high. The freshly exposed timber introduced more fuel to the fire resutling in the fire regrowth.

PRG 320 compliant CLT must pass a large-scale test designed to closely mimic the fire exposure from the FPRF tests where delamination and fire regrowth occurred. In the PRG 320 test a 2.8 m by 5.8 m by 2.4 m compartment is constructed with a fully exposed CLT ceiling loaded to 25% of the allowable design stress of the panel. Instead of a specified fuel load from furniture, a temperature profile in the compartment is specified and the fuel flow must be calibrated to meet this profile. The heat release rate of the burner used in previous testing is shown in Fig. 1. To become certified, the panel must sustain the load for the entire 240 min test and no fire regrowth can be observed after 150 min with temperatures at the ceiling of the compartment remaining below 510 °C.

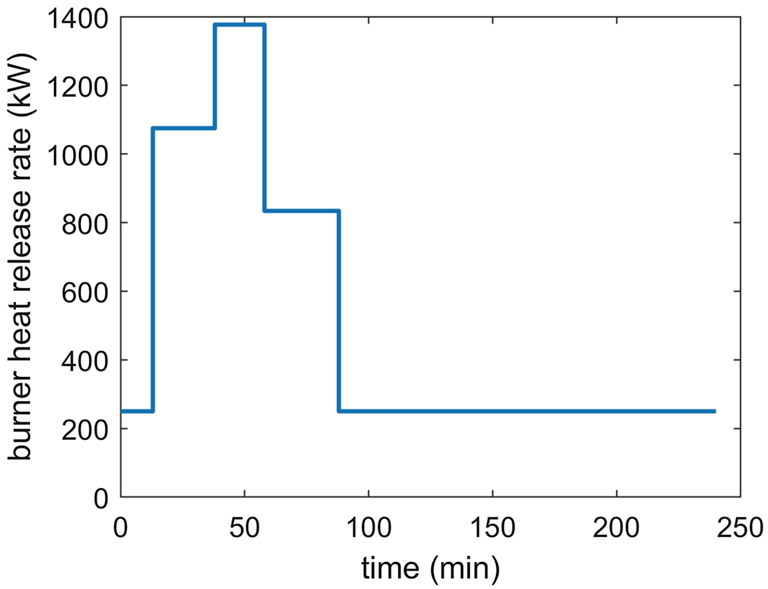

Fig. 1. Heat release profile for the burner used in the PRG 320 test [3]. To pass, the CLT must not cause any temperature increases in the compartment after 150 min.

While the PRG 320 test is the current standard for entrance to the marketplace, it is an expensive test and cannot be used for screening different adhesives nor understanding how different chemical changes to adhesives affect their fire performance in

CLT. In both the PRG 320 test and the FPRF tests, the temperature at the bondlines increased time and the rate of this increase can be closely approximated by a secant line drawn through the minimum measurable temperature and the peak temperature or temperature at failure. Therefore, it should be possible to scale down the physics of the test to a single bondline.

Small, scaled-down tests would be invaluable in the development and screening of new adhesives. Previous work has examined quasi-static testing at elevated temperatures [5, 6]. While the quasi-static test was useful in understanding the reduction in strength as a function of temperature, the loading conditions are not directly applicable to the PRG 320 standard. This paper discusses a scaled-down test designed to match the bondline temperature profile and loads of the PRG-320 test.

2 Development of Creep Test

The creep tests were designed to be representative of the physics of previous large scale compartment fire tests where delamination was observed; namely the FPRF tests and PRG 320. The temperature ramp rates were prescribed to match the bondline temperature profiles reported in the tests. Furthermore, the loads were scaled to match the shear stress at the bondline for the sample geometry used in previous quasistatic testing to that used in the PRG 320 and FPRF tests.

2.1 Sample Materials and Geometry

The specimens consisted of a single stepped-lap shear joint and were constructed from Douglas fir. The half-lap was created with the use of a router and samples were glued within 3 h of machining per the manufacturers' procedure. The sample had a bonded area of 565 mm^2; full sample details are described elsewhere [5, 6].

2.2 Temperature Profile

The bondline temperature profiles from the PRG 320 tests are shown in Fig. 2 for a melamine formaldehyde (MF) adhesive and two different polyurethane (PUR formulations). For the adhesives that passed the test, (MF and PUR2, both shown in blue) the first bondline remained below the char temperature of wood for the entire test. However, for the adhesive that delaminated (PUR1), the first bondline failed during the first part of the test when a high amount of fuel was being added to the fire. In this test, it was the second bondline that failed and caused fire regrowth. In all three tests, the temperature at the critical bondline exhibited a nearly linear increase in temperature with respect to time. The slope of the temperature increase at the bondline varied from 3.0 °C min^{-1} for the MF adhesive at the first bondline to 5.2 °C min^{-1} for the second bondline of the PUR1 adhesive. The slope of the temperature rise at the first bondline of the PUR2 adhesive was 4.0 °C min^{-1}.

Figure 2 compares the bondline temperatures from the FPRF test with the exposed ceiling and PRG 320 test. Both tests used panels made at the same manufacturing plant with the same adhesive. The temperature rise at the first bondline is nearly identical between the two tests. However, the second bondline heated at a slower rate in the FPRF test than in the PRG 320 test. In the FPRF test, the bondline temperature increased by 2.0 °C min^{-1}. Interestingly, the bondline failed at a lower temperature (232 °C) than in the PRG 320 test (>270 °C).

In summary, in previous compartment fire testing, the temperature has been found to increase linearly with time at the bondline. The rate of the linear increase has varied from 2 to 5 °C min^{-1}.

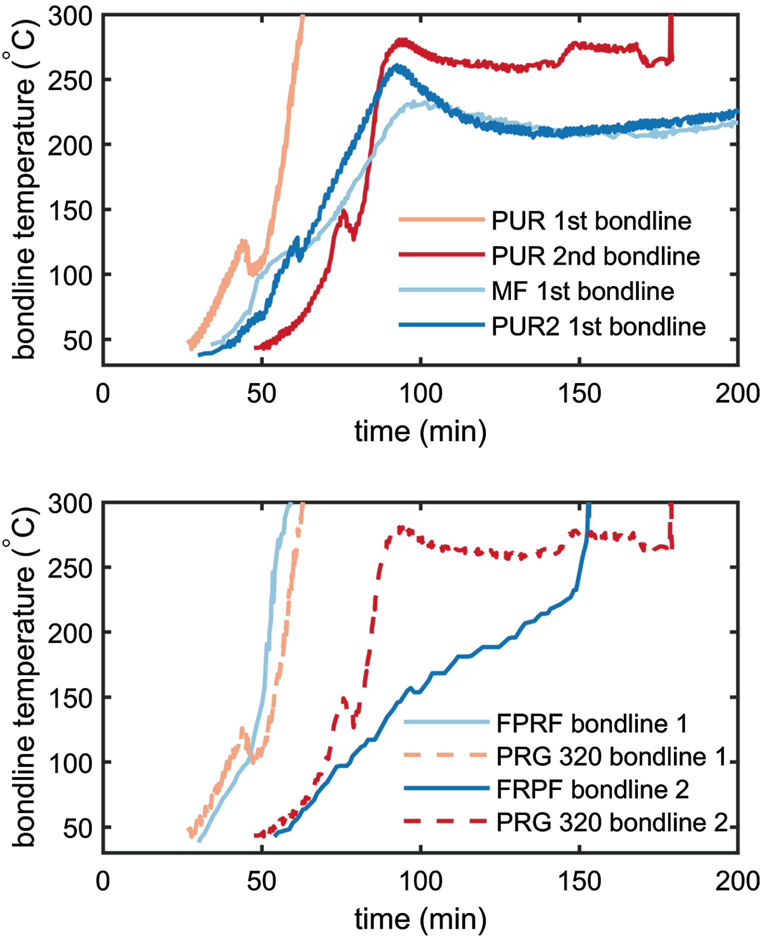

Fig. 2. Top: Bondline temperature profiles from the PRG 320 test for a melamine formaldehyde (MF) adhesive along with two polyurethane (PUR) adhesives. Bottom: Comparison of bondline temperature profiles in the FPRF and PRG 320 tests for a polyurethane adhesive labeled PUR1 in the top graph. Data replotted from [4] and [7].

2.3 Load Profile

Similar to the temperature profiles, the creep tests were conducted such that the shear stress at the bondline for the specimen would match the state of shear stress at a bondline for a panel in bending per the FPRF or PRG 320 procedures. The values were estimated as the shear stress due to bending at the first (outermost) bondline in the tensile region using classical beam theory.

For the FPRF tests, a deadload was applied at two points along the panel length, creating the equivalent of four-point bending about the major axis of the panel. The corresponding shear stress at the first bondline for a 5-ply panel was estimated to be 12 kPa. The PRG 320 test specifies a loading of 25% of the effective allowable design stress. For a V1 grade 5-ply CLT, this results in a shear stress at the first bondline of 53 kPa. The shear stress at the bondline for the specimen is assumed to be uniformly distributed over the bond area of 565 mm^2.

3 Planned Testing

Six adhesives will be tested: two formulations of PUR, two formulations of emulsion polymer isocyanate (EPI), one formulation of MF and one formulation of phenol resorcinol formaldehyde (PRF). All adhesives will be tested in a quasi-static method at room temperature and at 260 °C. These quasi-static tests will be used to benchmark adhesive performance and be used to investigate potential differences between the adhesive performance under various loading conditions.

Creep tests will also be performed. Two different temperature ramp rates will be examined, a slow temperature ramp of 2 °C min^{-1} ramp based upon the FRPF test and a 4 °C min^{-1} ramp based upon the observed temperature increases in the PRG 320 tests. In these tests the temperature ramp will be controlled based upon a thermocouple embedded to the mid-depth of the sample outside of the gauge length and therefore the temperature ramp should correspond with the bondline temperature. Based upon the observed failures in the PRG 320 and FPRF tests, it appears that the 2 °C min^{-1} test will be more challenging.

The applied load on the tests will also be examined as an experimental variable with tests being performed to match the stresses in both the FPRF and PRG 320 tests.

In total, four different tests will be performed on each of the six adhesive formulations:

- Quasi-static testing at room temperature
- Quasi-static testing at 260 °C
- Creep testing at 2 °C min^{-1} and a bondline stress of 12 kPa
- Creep testing at 4 °C min^{-1} and a bondline stress of 53 kPa

For adhesive formulations that do not exhibit failure in the creep tests will the low bondline stresses associated with the PRG-320 loading, additional creep testing may be performed at higher loads. While it is assumed that these adhesives have a high probability of passing the PRG-320 test, the goal of these additional tests is to better understand the failure mechanisms of these adhesives.

4 Discussion and Concluding Remarks

Currently, large-scale qualification tests are needed before adhesives can enter the marketplace which can be cumbersome, time consuming, and expensive with little data gathered beyond a pass/fail criterion. To this end, this project is examining how small-scale tests can be used to better understand adhesive performance at elevated temperatures and screen adhesives to avoid costly, large-scale testing.

In previous large-scale compartment fire testing, the temperature rise at the bondlines in CLT has been linear, with a rates between 2 to 5 °C min^{-1}. The planned tests will examine the behavior of single stepped-lap shear joints under the same temperature ramp as those seen in the large-scale tests. The small-scale testing will aid in the development of new adhesive formulations and improve the understanding of the fire performance of CLT.

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