ABILITY OF FINGER-JOINTED LUMBER TO MAINTAIN LOAD AT ELEVATED TEMPERATURES[1]

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Abstract. This article presents a test method that was developed to screen adhesive formulations for finger-jointed lumber. The goal was to develop a small-scale test that could be used to predict whether an adhesive would pass a full-scale ASTM E119 wall assembly test. The method involved loading a 38-mm square finger-jointed sample in a four-point bending test inside of an oven with a target sample temperature of 204°C. The deformation (creep) was examined as a function of time. It was found that samples finger-jointed with melamine formaldehyde and phenol resorcinol formaldehyde adhesives had the same creep behavior as solid wood. One-component polyurethane and polyvinyl acetate adhesives could not maintain the load at the target temperature measured middepth of the sample, and several different types of creep behavior were observed before failure. This method showed that the creep performance of the one-component adhesives may be quite different than the performance from short-term load deformation curves collected at high temperatures. The importance of creep performance of adhesives in the fire resistance of engineered wood is discussed.

Keywords: Heat durability, adhesives, finger-jointed lumber, fire resistance, heat transfer.

INTRODUCTION

The ability of assemblies to maintain their integrity when exposed to a standard fire exposure, measured in units of time, is referred to as the fire resistance rating (Buchanan 2001). In the United

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States, the fire resistance rating is typically determined by exposing a loaded assembly to an ASTM E119 time-temperature curve (Anon 2014). Although wood is a combustible building material, when exposed to fire, wood undergoes pyrolysis, leaving behind a layer of char, which is an insulating layer that protects the underlying material (White and Dietenberger 2010). Based upon theory and measurements, the reduced cross-section analysis methodology has been developed for calculating the residual strength of a wood member under fire (White 1995; Anon 2003). The reduced cross-section analysis method assumes that the char layer and the layer of wood immediately beneath the char layer have zero strength, and that the load is carried by the rest of the member. Although the reduced cross-section analysis is well-suited for solid wood, engineered wood and finger-jointed lumber have nonhomogenous properties, and the residual strength depends upon the properties of both the wood and the adhesive properties at elevated temperatures (Frangi et al 2004).

The performance of wood adhesives under elevated temperatures (fire scenarios) has been studied since the 1960s in seminal work by Schaffer (Schaffer 1968). Schaffer placed wood bond lines under a burner and afterward cross-sectioned the bond lines to observe the char pattern around the bond line. The residual bond strength was also measured. Schaffer observed that melamine formaldehyde (MF) and phenol resorcinol formaldehyde (PRF) adhesives did not separate from the char layer and the fire front moved through these adhesives similar to solid wood. For many years, the fire performance of engineered wood composites was not a concern, as phenolic-based adhesives were widely used and known to break down at temperatures higher than the charring temperature of wood (Yeh et al 2005).

In 2007, the wood industry discovered that wall assemblies constructed with finger-jointed lumber manufactured with certain adhesives did not achieve a 1-h fire resistance rating when tested per ASTM E119. As a result of this testing, industry instituted new regulations for finger-jointed lumber, creating a heat-resistant adhesive, or "HRA", class of finger-jointed lumber that could be used in any application, and a second class that could only be used in nonfire resistance-rated assemblies (Anon 2007). To be classified as HRA, the finger-jointed lumber must achieve a 1-h fire resistance rating in an ASTM E119 fire exposure where the lumber is placed in a stud-wall assembly at 100% of the design load as described in ASTM D7247 (Anon 2016b).

Because of the high cost of full scale wall fire tests, it was desirable to develop a small scale, laboratory screening test that could predict whether a new adhesive formulation was likely to pass a full scale wall test. This paper summarizes a small scale test method developed in 2007 at Forest Products Laboratory to screen the performance of adhesives for finger-joint applications. The delay in publication is a result of a confidentiality period on the funding agreement. However, with the recent interest in the fire performance of adhesives used in cross-laminated timber (CLT), the methodology and findings from this study have increased relevance.

MATERIALS AND METHODS

Materials

Samples were made from machine rated ($2100F_{yb}$) Douglas fir nominally 50 mm by 150 mm. Samples were jointed on one narrow face and then ripped, so that the final dimensions were 38 mm by 38 mm. Finger joints with a 16 mm profile were cut using an AceCo Precision Manufacturing Company C16-275/276 cutter (Boise, ID). The adhesive was applied within 3 h of cutting the finger joint and then was placed into a fixture and clamped according to the time and pressure specified by the adhesive manufacturer. A representative finger joint is shown in Fig 1.

Eight different adhesive formulations were tested from three adhesive manufacturers. Five replicates were tested for each formulation. The adhesives fell into four major classes: one-component polyvinyl acetate (PVA), one-component polyurethane (PUR), two-component MF, and two-component PRF.

Figure 1. Representative finger joint made in the laboratory.

Four PUR adhesives were tested from two different manufacturers. Two different PVA adhesives were tested from the same manufacturer. Only one formulation of PRF and MF were tested.

Before testing, specimens were dried at 104°C for 24 h, and then maintained at 30°C and 20% RH. Samples were predried to remove the thermostatic dwell at 100°C caused by dehydration during heating. Immediately before testing, specimens were cut to 812 mm in length, and the ends were then used to determine the MC and specific gravity. Pretest MC and specific gravities for each treatment are given in Table 1.

Table 1. Average pretest MC and specific gravity calculated from oven dry volume and mass.

	MC (%)	Specific gravity (g/g)
Douglas fir (solid wood)	1.93	0.46
PRF	2.06	0.49
MF	2.39	0.47
PVA-1	2.41	0.54
PVA-2	1.96	0.56
PUR-1	2.31	0.47
PUR-2	2.15	0.51
PUR-3	2.18	0.51
PUR-4	2.44	0.51

PVA, polyvinyl acetate; PUR, polyurethane; PRF, phenol resorcinol formaldehyde; MF, melamine formaldehyde.

Methods

The test method consisted of placing finger-jointed lumber under constant load in four-point bending at elevated temperature (204°C target temperature). The temperature and loading profiles were chosen based upon data collected from ASTM E119 wall tests of finger-jointed studs. Figure 2 presents the lateral deformation collected in two different wall tests along with a schematic representation of the deformation. It can be seen that a bending moment is generated by the P-Δ effect that arises from both the shrinkage of the wood and reduction of cross section caused by charring. Significant deformation levels are observed after 50 min, and the behavior in the last 10 min of the test is critical to the survivability of the 1-h wall test.

Although Fig 2 shows the deformations observed in the wall test, to determine the appropriate stress level to apply in the small-scale test, knowledge of the residual cross section of the wood stud as necessary. The reduction of cross section during an ASTM D7247 fire test was modeled, and the temperature profile is shown in Fig 3. The model consisted of a two-dimensional finite-element model called CUWoodFrame, which simulated the heat transfer through the wood stud (Craft 2009). The boundary conditions on each surface of the stud used temperatures measured in a full-scale wood stud wall fire resistance test built as specified in ASTM D7247 with one layer of 5/8″ Type X gypsum board on each side and mineral wool insulation in the stud cavities. The temperatures measured on the surfaces of the stud during the ASTM E119 standard fire exposure were used to provide the most accurate boundary conditions possible to predict the temperature gradients within the stud as a function of time. The stresses at various times were calculated, assuming that the wood in excess of 288°C had charred and the char front could be approximated at half an ellipse. It was further assumed that the pyrolysis zone in front of the char layer provided little additional strength, so the zone of degrading or zero strength was 20% greater than the char front. Based on these assumptions, the deflection profiles, and a load per stud of 8006 N, the combined stress level on the studs calculated as a function of time (Fig 3b) for the solid sawn and

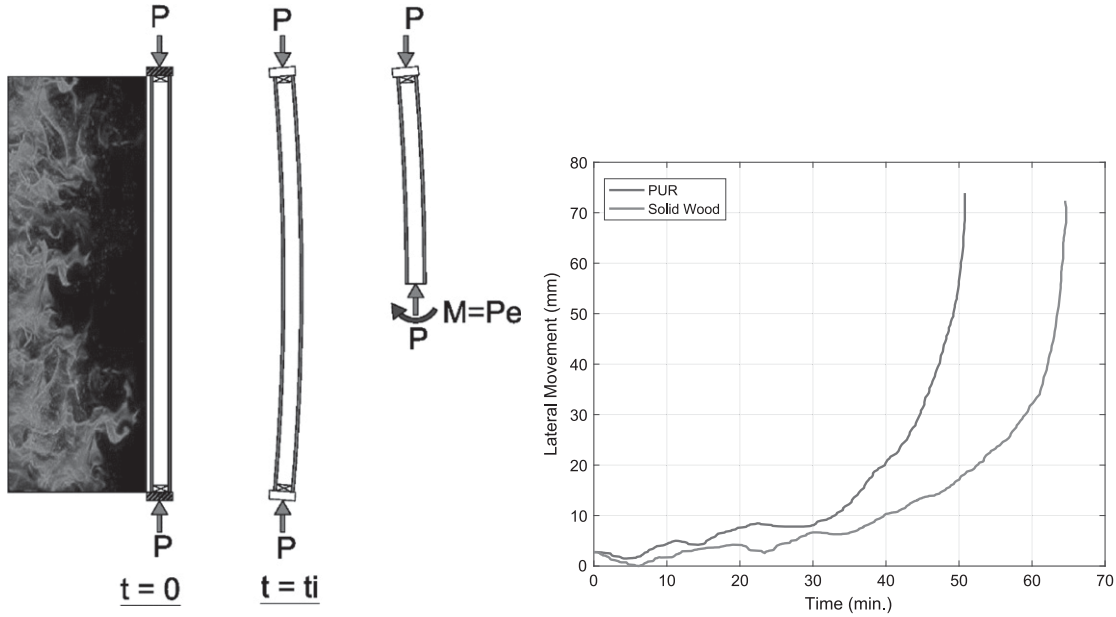

Figure 2. Mechanics and deformation states of a 1 h E119 fire test for a solid sawn and finger jointed light frame wall tests.

finger-joint E119 wall tests. Based on this analysis and additional proprietary wall test information, a target stress level of 10.3 MPa was determined as an appropriate value for the screening test method. The tests were conducted for 2 h or until the failure, which was deemed to have occurred when there was a sudden increase in midspan deflection as a result of a failure of the finger joint.

The temperature of the wood was measured with type T thermocouples. Three thermocouples were embedded to the middepth of the wood, and three thermocouples were embedded at the specimen surface along the neutral axis. Two of the three middepth thermocouples were placed 38 mm from both sides of the center of span, near the edges of the finger joint. The other reading was taken at the middepth over one of the end supports. Each of

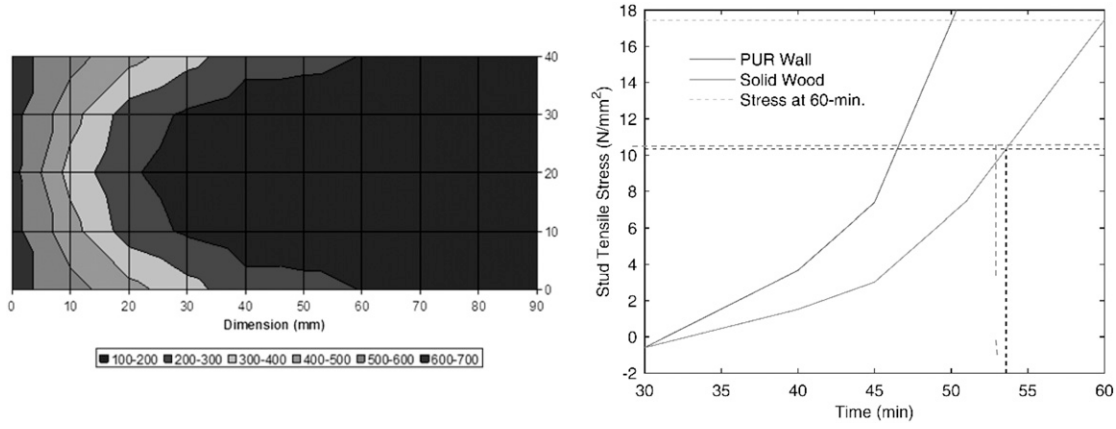

Figure 3. Thermal profile of light frame wall after 40 min of ASTM E119 exposure and the associated cool side stresses of the remaining wall section.

the middepth thermocouples was paired with a surface thermocouple. The two middepth thermocouples near the finger joint were averaged to get the middepth or "bond-line" temperature. The oven temperature was monitored with two additional thermocouples placed within the oven.

The samples were exposed to a constant load of 680 N applied in a four-point bending test. This results in a bending moment that represented the 53rd min of a solid sawn stud wall test. The span was 760 mm, and the load was suspended from two loading points that were 280 mm from each end. The applied bending stress was 10 MPa. The deformation was measured with a $\pm$ 6 mm linear variable displacement transducer (LVDT) that was placed outside of the oven to reduce the effect of heat on the electronics and ensure a stable reading. A fused silica rod was used to extend the core of the LVDT to the specimen. Fused silica was chosen for its low thermal conductivity and extremely low coefficient of thermal expansion. Figure 4 shows a sample with thermocouples placed in the loading device in the oven with the fused silica rod at midspan.

The target test temperature was 204°C at the two thermocouples placed at the middepth near the finger joint. This temperature was chosen to minimize any strength loss caused by wood degradation and to focus on performance of the finger joint. Although the goal of the test was to observe the behavior of the finger joint at 204°C, it took significant time for the thermocouple at the midspan, middepth of the sample to reach the target temperature. Through experimentation, a heating protocol was developed to reduce the time required for the middle of the sample to reach 204°C to 60 min. This was accomplished by first preheating the oven and loading device to 235°C before placing the specimen in the oven and loading it ($t = 0$). The oven set point remained at 235°C until the oven temperature reached 225°C, at which the set point was reduced to 225°C until the middepth of the samples reached 185°C. Once the middepth of the samples reached 185°C, the oven temperature was reduced to 204°C for the remainder of the test or until the sample failed. Because the total time of the test was 2 h, if failure did not occur, the sample remained at the target temperature for roughly 1 h. As a result of driving, the oven at temperatures above the 204°C target, specimen surface temperatures were in excess of the target temperature. The maximum surface temperature was always less than 220°C.

Figure 4. Sample and loading device in the oven. To load the specimen, the lever arms were brought down to rise to steel plates and apply a bending stress of 10 MPa. The load was applied normal to the plane where the fingers of the finger joint were visible.

To get baseline data on the performance of the adhesives under room temperature, static bending tests were conducted according to ASTM D198 (Anon 2005). The static bending tests were conducted with the same span and load points as the high temperature tests. The tests were conducted under displacement control, and the loading rate was selected so that the specimens failed between 5 and 10 min after the application of the load. The modulus of rupture (MOR) was between 40 and 55 MPa for the adhesive systems and 69 MPa for solid wood. In the high-temperature experiments, a constant stress equivalent to 10 MPa was applied to the specimen; this is equal to 14-25% of the MOR at room temperature depending on the adhesive system.

RESULTS

The temperature profile range as a function of time for Douglas fir samples are shown in Fig 5.

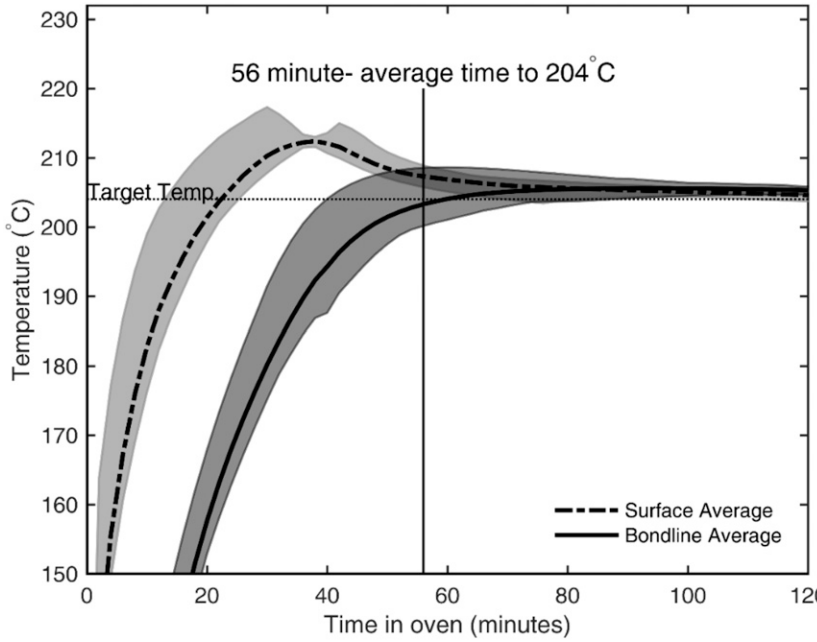

Figure 5. Temperature profile as a function of time for solid Douglas fir samples.

The two lines represent the average surface and middepth (bond-line) temperature; the shaded regions represent the maximum and minimum ranges from the replicates. When the bond line reached 185°C, the temperature in the oven was reduced to 204°C. On average, it took 56 min for the bond line to reach 204°C.

Figure 6 shows the deformation ratio (deformation normalized to the initial deformation) as a function of time for 1) solid wood , 2) PRF 2), and 3) MF 3). By normalizing the deformation to the initial deformation, differences in stiffness between replicates are minimized, and the creep behavior can more clearly be seen (Anon 2016a).

Figure 6d plots the performance of PRF and MF with the solid wood data. It can be seen that there was no difference in the mean creep behavior for solid wood and finger-jointed wood made with PRF or MF. In all cases, the data exhibited the 1st two stages of a classical creep behavior (Callister 2003). In the 1st 60 min, the sample underwent primary creep where there was a high initial strain rate that slowly decreases. For the 2nd h of the test, the deformation increased slowly and linearly with time at a constant strain rate, which is the hallmark of secondary creep.

Figure 7 presents the normalized behavior as a function of time for the one-component adhesives. The average behavior of solid wood is shown in each graph for reference. Unlike Fig 6, the time axis is compressed in Fig 7, as none of the samples in Fig 7 lasted longer than 30 min.

Two different types of behaviors can be observed. In Fig 7b, the finger joint exhibits similar creep behavior to the wood until the adhesive fails. In Fig 7c and f, the samples exhibit more deformation at lower temperatures before failure. In Fig 7a, d, and f, it appears that some replicates exhibited similar deformation, as wood and other replicates had more creep before failure.

All one-component adhesives failed at the finger joint. Figure 8 shows a typical failure surface. The finger joint failed with no wood failure. The remaining surfaces of the finger joint appeared to be in good condition and could easily have been reglued (Fig 9).

The failure temperatures for the one-component adhesives are shown in Fig 10. For PVA-2 and

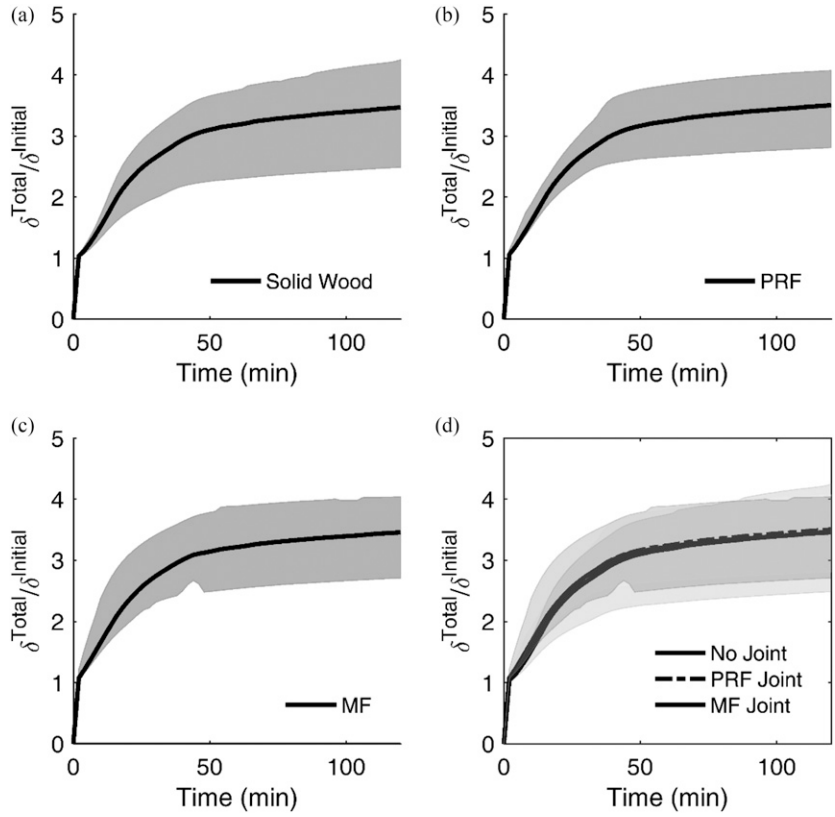

Figure 6. Deformation as a function of time for (a) solid wood, (b) finger joint made with PRF, and (c) finger joint made with MF adhesive; (d) shows the data from (a-c) overlaid on the same graph. The solid line represents the average behavior of five replicates, and the shaded region shows the range of observed behaviors. The *y*-axis represents the deformation normalized to the initial deformation.

PUR-3, the surface of the sample reached the target temperature of 204°C before the sample failed. While none of the tested one-component adhesives could withstand a sustained load with a middepth temperature above the target temperature of 204°C, the data in Fig 10b can be used to get a relative comparison of the performance of the adhesives. From these data, it appears that the PVA-2 and PUR-3 are the most able to resist load at high temperatures.

DISCUSSION

The original goal of this work was to develop a test method to screen potential finger-joint adhesives in the laboratory before taking them to a commercial test laboratory for a full-scale fire resistance wall test. The goal was not to fully simulate an ASTM E119 wall test but instead differentiate between adhesives using a low-cost test while still approximating the wall behavior. While the stress on the finger joint was derived from a calculation of the loading on an ASTM E119 wall test, the exact exposure could not be easily replicated because in a real fire exposure, the wood studs are under eccentric thermal and mechanical loads (König et al 2008; Frangi et al 2012; Klippel et al 2013).

After these experiments were conducted, there has been much research on the performance of adhesives and finger joints at high temperatures and fire exposures (Frangi et al 2004; Craft et al 2008; König et al 2008; Tannert et al 2009; Clauß et al 2011a,b; Frangi et al 2012; Klippel et al 2013; Lehringer and Gabriel 2014). Although the

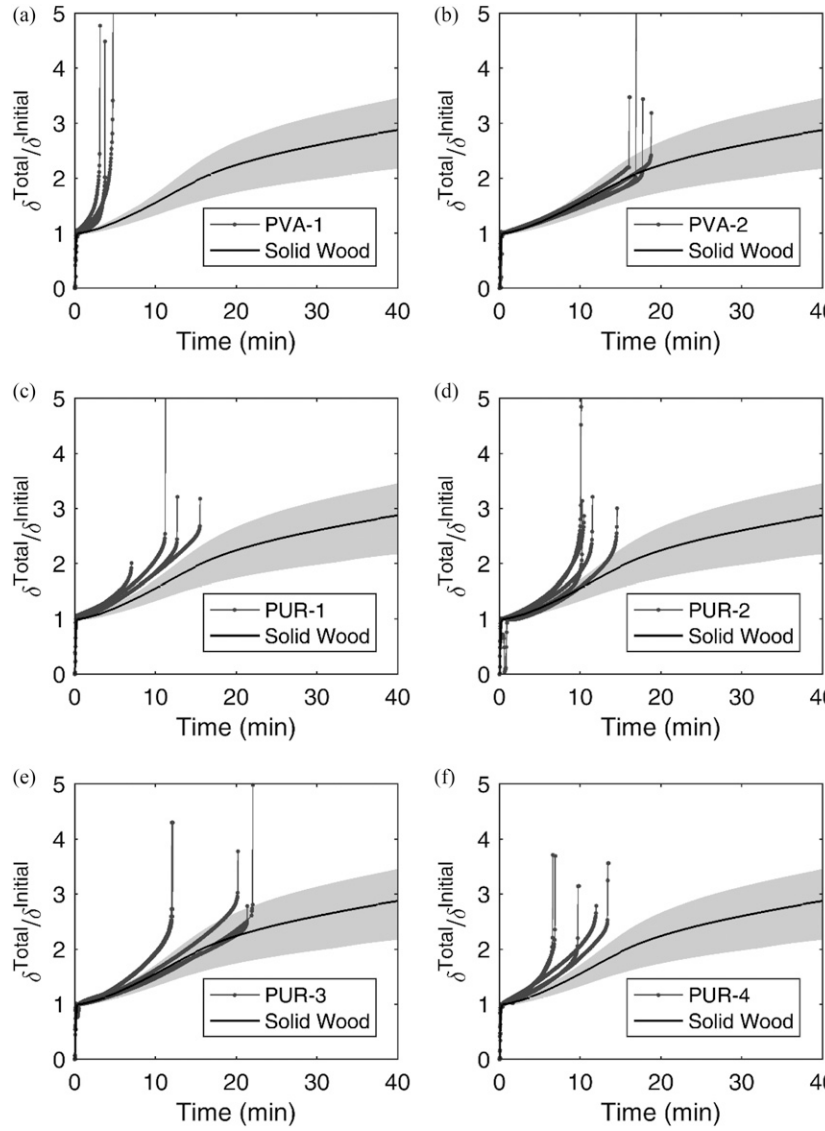

Figure 7. Deformation as a function of time for finger joints made with (a) PVA-1, (b) PVA-2, (c) PUR-1, (d) PUR-2, (e) PUR-3, and (f) PUR-4. The behavior of solid wood is included on the graph for reference. The *y*-axis represents the deformation normalized to the initial deformation. PVA, polyvinyl acetate; PUR, polyurethane.

majority of the research has shown that traditional, phenolic wood adhesives perform better than one-component PUR above 150°C, in general, differences from previous work are not as pronounced as the differences observed in this work. For instance, Clauß et al found that PUR formulations had 80-95% of the shear strength of PRF at 200°C (Clauß et al 2011b). In a four-point bending test similar to this work, Frangi et al found no difference in bending strength between adhesives up to 140°C (Frangi et al 2012). Using the standard fire curve, König et al (König et al 2008) found that glulam with PUR and MUF finger joints on the tension lamination had 70-80% of the bending strength of glulam made with PRF in fire exposures.

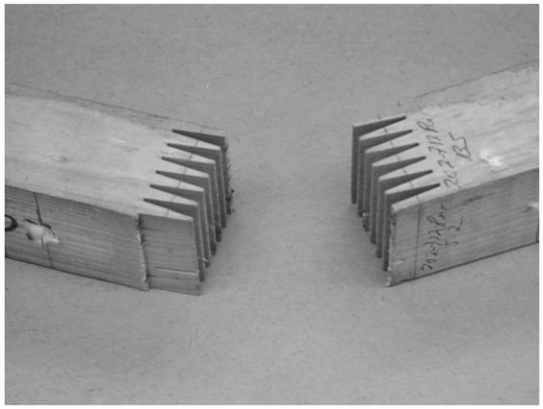

Figure 8. Typical failure surface of a finger joint made with a one-component system after failure.

The only other paper to find a dramatic difference between one-component PURs and phenolic wood adhesives was the work of Craft et al (2008). It should be noted that this effort was coordinated with that of Craft et al and used matched samples. Similar to this work, Craft et al performed a creep test of finger-jointed lumber under constant load at high temperatures. However, Craft et al tested the joints in tension and used thinner specimens that reached the equilibrium temperature (of 220°C) more rapidly. Lehringer and Gabriel (2014) noted that the method of Craft et al was unrealistic and overly harsh because in a fire, there would be a steep thermal gradient and very little of the finger joint area would be at or above 220°C. However, it should be pointed out that the method of Craft et al was used to differentiate performance between adhesives, and any duration of exposure could be chosen as failure criteria, not necessarily the full 2-h exposure. Although that criticism related to the lack of a significant thermal gradient may be of concern for the work of Craft et al in these experiments, there was a 50°C gradient from the outside to the middle of the sample, and PUR joints failed at interior temperatures between 90°C and 175°C.

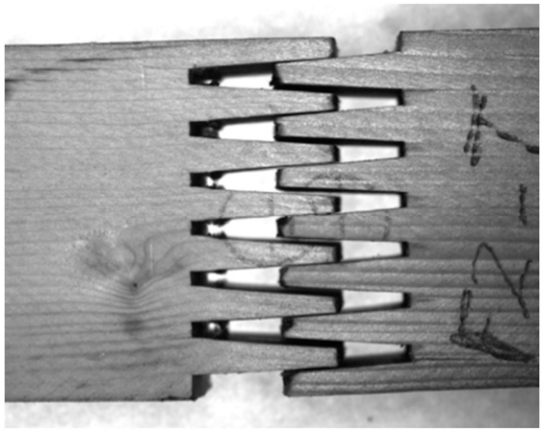

Figure 9. Finger joint after failure showing smooth wood surfaces that could be easily refit together.

Overall, two different behaviors have been observed with PUR adhesives at high temperatures. In short-duration (1-5 min) tests, wood joints made with PUR adhesives have only slightly lower strength (approximately 70-95%) than a joint made with traditional wood adhesives such as PRF. However, in creep tests, where a constant load is applied and it is exposed to high temperature, the PUR adhesives perform significantly worse than traditional adhesives. This suggests that while the wood joints made with PUR adhesives retain much of their elastic strength at high temperatures, the viscoelastic properties of these adhesives may decline rapidly at high temperatures.

Current results suggest that creep performance of PUR and PVA adhesives are lower than their traditional two-component wood adhesive counterparts at elevated temperatures. This raises questions on what kinds of small-scale tests can help understand the performance of adhesives under realistic fire exposures and/or qualify them for use in wood product manufacturing. In an ASTM E119 wall test, finger-jointed lumber must maintain the load as the cross section is reduced and the temperature of the remaining cross section is increased. In theory, this loading scenario is more closely represented by a creep test than by measuring the immediate strength at various temperatures. Although it may be possible to use a similar method to predict the performance of finger-jointed lumber in fire tests, the temperature ramp rate and applied load in this test may not perfectly match what would be expected from the wall test. Further tuning of the temperature and

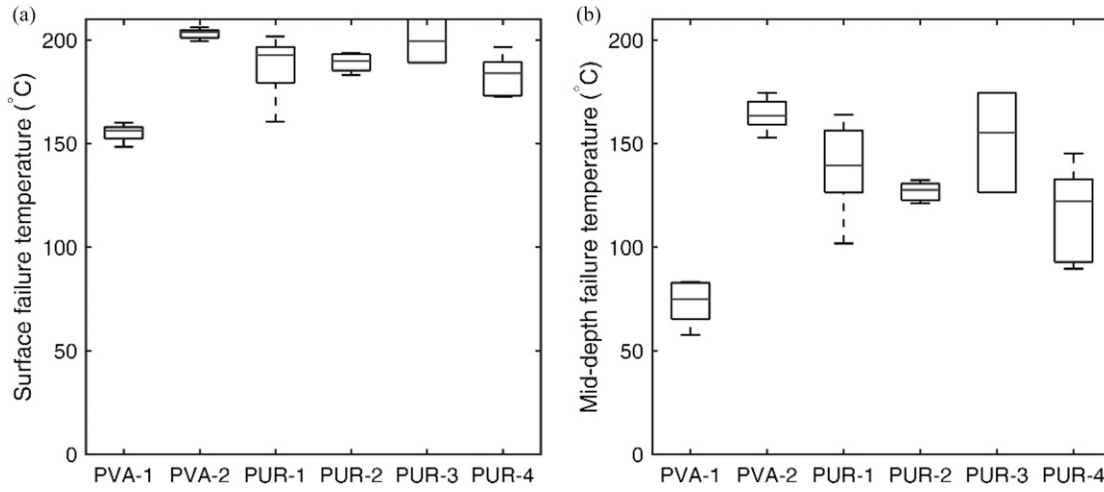

Figure 10. Surface (a) and middepth (b) failure temperatures for the one-component adhesive systems tested.

loading may improve the correlation with wall test results.

Currently, there are efforts to understand delamination in CLT and develop qualification tests for adhesives used in CLT within the ANSI/APA PRG-320 performance standard. In some CLT compartment fires, a second flashover has been observed, after the room contents have been consumed, caused by the delamination of CLT which exposes additional fuel to the fire (Gerard et al 2013; Brandon and Östman 2016). Similar to finger-jointed lumber, delamination depends upon the temperature, time, and stress placed upon the adhesive. However, unlike the finger joint where there is a gradient of temperatures on the adhesive joint, the interlayer adhesive in CLT is at a relatively uniform temperature that increases with time. The creep performance of the adhesive joint is likely a key attribute of whether the CLT delaminates.

Given this relationship, it may be possible to modify the method presented in this article to study delamination in CLT. The geometry of the test could be modified so that there is a lap joint loaded in shear. Delamination could then be determined from the temperature at which the sample failed in relationship to the temperature at which wood chars. This test should more closely mimic the failure mechanism than current standards for evaluating the performance of adhesives at high temperatures. For instance, the ASTM D7247 test is used to qualify adhesives for use in engineered wood products in the United States. In this test, a shear block is heated to 200-250°C and tested immediately (Anon 2016b). In the 2012 version of the ANSI-APA PRG-320 standard for CLT, the adhesives are tested by placing a plywood sample 25 mm from a Bunsen burner with a flame temperature of 800-900°C, and the bond lines are examined for delamination (Anon 2012). Neither of these tests capture the ability of the adhesives to maintain strength at high temperatures over a period of time as it occurs in a real fire scenario.

CONCLUSIONS

This article presented an experimental method for evaluating the performance of finger-jointed lumber at elevated temperatures. The goal of the test was to simulate the loading that would be expected on a wood stud in a wall assembly near the end of the test at a constant temperature of 204°C. Traditional two-component adhesives that contained formaldehyde had a similar response to solid wood. The one-component adhesives that were tested failed before reaching 204°C. Middepth failure temperatures ranged between 60°C and 175°C.

Although there are differences in the thermal and mechanical loading between finger-jointed studs and CLT walls or floors, the data may provide some insight into the delamination behavior of CLT. The failure temperatures for the adhesives that failed in these tests are indicative of potential delamination temperatures for CLT; therefore, modifications to this method could make it a suitable test for evaluating the potential for delamination in CLT.

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