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Intermediate-Scale Test Developed to Screen Adhesive Fire Performance in Glued-Laminated Timber before Full-Scale Testing

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Abstract

When a new engineered wood adhesive is developed for use in a fire-rated assembly, it must first pass a full-scale fire test, for example, a test in accordance with ASTM E119 in the United States. Although full-scale tests serve as the necessary entry to the marketplace, they are extremely costly and reflect the performance of the entire assembly and not just the adhesive. As a result, it is difficult to quantify differences in adhesive performance under elevated temperatures or fire conditions with these tests. Here, we present the results from a new test method developed at the USDA Forest Service, Forest Products Laboratory, to examine adhesive wood performance in glulam beams. The test is part of a larger research program for examining different adhesive formulations. The goals of the intermediate-scale test were to understand differences between adhesive formulations and to provide guidance regarding the performance for full-scale adhesive tests.

Keywords: fire testing; adhesive performance; standardization; building code development

Contents

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Intermediate-Scale Test Developed to Screen Adhesive Fire Performance in Glued-Laminated Timber before Full-Scale Testing

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Introduction

The building code uses fire-rated assemblies to assure the life safety of occupants during fire. Fire-rated assemblies are building components whose fire resistance has been measured in a standardized fire test. Typically, in the United States, this requires a full-size wall or floor system being tested under a mechanical load while exposed to a standard American Society for Testing and Materials (ASTM) E119 fire curve (ASTM 2014). The fire rating is determined from the time the fire is started until failure. Depending on the end use, fire resistance ratings from 15 min to 3 h may be necessary.

Although these standardized tests serve as a necessary entrance to the marketplace, they are time consuming and extremely costly to perform. These costs are compounded by the fact that small changes to the assembly, such as a change in the adhesive formulation in the engineered wood products, requires a new full-sized test. For example, for finger-jointed lumber to be used as studs in a wall assembly, each adhesive formulation needs to pass a full-scale wall test to achieve a heat resistant adhesive (HRA) designation (WWPA 2007, Yeh and others 2005). In 2017, the PRG 320 product standard for cross-laminated timber (CLT) added new requirements for examining the heat resistance of the adhesives used in CLT (APA 2017). To obtain PRG 320 certification, a full-sized compartment needs to be constructed and survive a several hour test with a burner profile based upon other large-scale fire testing in which delamination was observed (Su and others 2018).

The large costs associated with these certification tests make it difficult to learn about adhesive performance under fire and serve as a barrier to entry for new adhesive formulations. Small-scale tests, if scaled using the appropriate physics, can predict the likelihood of a component or assembly passing a full-scale test. These small-scale tests, therefore, will allow many different configurations to be screened prior to full-scale testing. Additionally, by testing many different samples, a richer picture of the failure mechanisms can be generated. Therefore, it may be possible to develop safer and more fire-resistant systems based upon insights gathered from small-scale tests.

For several years, the USDA Forest Service, Forest Products Laboratory (FPL), has been working on developing small-scale fire tests to understand adhesive performance (Miyamoto and others 2021, Rammer and others 2018, Zelinka and others 2018). In this report, we present work developing a scaled test to screen adhesives for the full-scale Canadian Standard Association CSA O177-06 glue laminated beam test (CSA Group 2006). The physics of how the test was scaled are presented. Example results from a beam made with a phenol-resorcinol-formaldehyde (PRF) adhesive demonstrate that failure times measured in this test correlate with the expected failure times of the CSA O177-06 test.

Materials and Methods

The CSA O177-06 standard is the product standard for glued-laminated timber in Canada. To become certified, adhesives need to pass two full-scale tests listed in Annex A.3, a column test and a beam test. This report focuses on developing a scaled test for the full-scale beam test (Annex A.3.3). In the CSA O177-06 beam test, a Douglas-fir, Grade 24f-E glulam with dimensions of 175 mm wide by 343 mm deep by 4,700 mm long is tested. The laminations are 38 mm thick, and the bottom three laminations are required to have an end-joint at midspan. The beam is uniformly loaded to lateral design loads determined in accordance with CAN/CSA-O86 (CSA Group 2019) and then exposed to the CAN S101-04 (ULC 2004) time–temperature curve in a furnace.

The CSA O177-06 standard is designed such that a solid beam will fail at 61 min. That is, assuming a char rate of 0.6 mm min^{-1}, the applied load will cause the remaining cross section to fail at 61 min. To pass the test, a glulam beam must survive at least 61 min, which demonstrates that the glued-laminated beam is at least as strong as solid wood under fire. Given the remaining cross section and thermal profile of the wood at 61 min in the full-scale test, it is likely that premature failures would occur in the finger joints. It is also possible that a failure could occur by delamination; however, such a failure would require the adhesive to lose strength at temperatures well below the char temperature of the wood.

FPL has an intermediate-scale furnace with inner dimensions of 1.83 m long by 0.99 m wide by 1.27 m tall. This furnace is heated by eight diffusion flame natural gas burners with a total capacity of approximately 275 kW. The FPL furnace was used to create a scaled version of the CSA O177-06 test. The same time–temperature curve was used and the beam cross-sectional size was maintained because of the fire dynamic requirement, but the length was shortened to fit in the smaller furnace with a corresponding adjustment in the loading profile. The beam length was controlled by the furnace and was limited to 3.45 m total length with the center 1.83 m heated. In CSA O177-06, it is specified that the load for the standard beam be determined in accordance with CAN/CSA-O86 for standard term duration of loading and a live-to-dead ratio of 4. The four-point loading scenario for the scaled beam was determined by matching the bending stress and shear stress present in the full-scale beam as specified in CAN/CSA-O86. It was determined that a four-point loading scenario with 49-kN loads 1.22 m apart as shown in Figure 1 would appropriately match the standard test.

A schematic of the test setup is shown in Figure 1. The beam was loaded by building a self-reacting frame around the horizontal furnace. The load was applied by two hydraulic cylinders, and the load was measured at each load point through load cells in line with the cylinders. The test frame could be easily disassembled, allowing the beam to be removed from the furnace within 5 min of failure for detailed post-test char rate measurements. The deformation was measured at midspan using a string potentiometer. This measurement assisted in determining when the failure of the beam occurred, either by shear (delamination) or bending. The furnace temperature was controlled to the standard time–temperature curve based on the readings of six thermocouples inside 21.3-mm OD by 15.8-mm ID Inconel 600 pipes (Special Metals Corporation, New Hartford, New York, USA) within the furnace. The temperatures inside the furnace, deformation, and load at each actuator were recorded by a computerized data acquisition system at 5-s intervals.

Special glulam beams with no finger joints were made for testing. The beams were made from solid lamination stock with no end joints. Therefore, the only potential mechanism for a premature adhesive failure was the failure of the face lamination. To validate the method and determine how closely the failure times matched the full-scale test, additional glulam beams were made with a PRF adhesive. PRF has been shown to have an equivalent strength to solid wood as it approaches the char temperature (Zelinka and others 2018). Furthermore, Schaffer (1968) observed that the char front moves through wood with a PRF joint in the same manner in which it moves through solid wood; that is, there is no preferential charring or opening along the joint. By testing the PRF beam, we were able to measure the time to failure of a theoretically "solid" beam. Three PRF beams were tested, and the results were compared with two beams made with the experimental adhesive.

Results and Discussion

Figure 2 presents the deformation ratios as a function of time data for the PRF glulam and the glulam made with an experimental adhesive. The deformation ratio (deformation normalized to the initial deformation) was used because this minimized any differences in initial stiffness among the wood material used in the tests (ASTM 2016). Time is presented as the elapsed time from when the furnace started the time–temperature profile. As a result, the initial load was applied before $t = 0$. The responses display classic, three-stage creep behavior. Initially, there was a steep increase in displacement as the load was applied ($t < 0$, data not shown). The displacement then proceeded at a steady state until tertiary creep was reached, and then the displacement increased rapidly until failure. While the beams made with PRF adhesive experienced more relative displacement, they were able to maintain load several minutes beyond the expected failure time of 60 min. All PRF beams tested lasted longer than 60 min. The experimental adhesive beams exhibited less deformation and a lower creep rate. They failed between 60 and 61 min.

A summary of the observed failure times is shown in Figure 3 from three PRF beams and two experimental adhesive beams. The average failure time for the PRF beams was 68 min. The full-scale test is designed such that a solid beam (or a beam made with PRF) should fail at approximately 61 min. The assumed char rate for the calculated failure time in the test is conservative, and the standard notes that solid beams may in fact last longer than 61 min. With no full-scale testing data available for a PRF beam, any direct comparison is not possible, although it appears that failure times for the presented test may be equivalent to the full-scale test or potentially slightly higher. The presented test is useful in screening various adhesive formulations and will only become more valuable in screening equivalent materials for future full-scale testing. Although success at the full-scale test cannot be guaranteed, if an adhesive formulation does not reach 60 min in the intermediate-scale test presented here, it is not likely to pass the full-scale test.

Our calculations suggested that failures would occur in finger joints during the full-scale tests. The presented experiments investigated adhesives used on face laminations. An additional failure mechanism was observed upon examining the beams after the experiment. The char

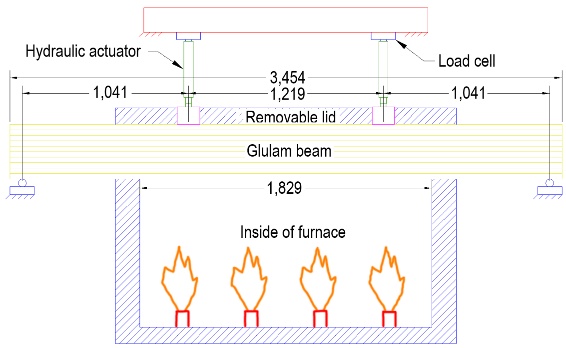

Figure 1. The intermediate-scale CSA-O177-06 test. Listed dimensions are in millimeters.

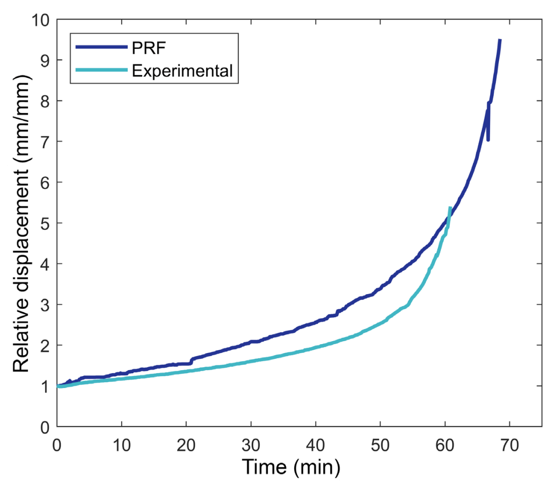

Figure 2. Example load deformation curves for the phenol-resorcinol-formaldehyde (PRF) and experimental adhesive beams.

patterns on the beams showed differences between the PRF and experimental adhesive beams (Fig. 4). For the PRF beam, the char moved equally through the cross section. For the experimental adhesive beam, increased charring could be observed at each of the laminations. This additional reduction in cross-sectional area may explain the differences in failure times between the PRF and the experimental adhesive beams, instead of it being caused by a rolling-shear failure at a bondline.

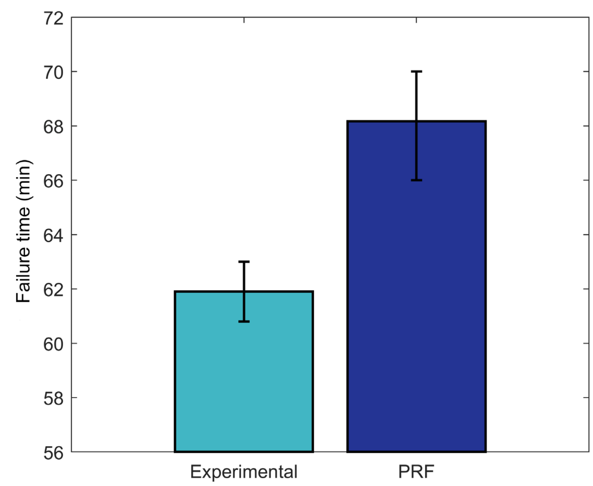

Figure 3. Failure times observed for the phenol-resorcinol-formaldehyde (PRF) and experimental adhesive beams. The error bars represent the maximum and minimum failure times.

Figure 4. Cross-sectional area at the end of the test for a glulam beam made with an experimental adhesive (left) and a phenol-resorcinol-formaldehyde (PRF) adhesive (right). The scale bar (top of image) is 50 mm long.

Summary and Conclusions

In this study, we examined the possibility of scaling the CSA O177-06 glued-laminated beam fire test to an intermediate scale. The goal was to develop a method to screen adhesives before full-scale qualification testing. PRF beams had an average test endurance of 68 min in the intermediate-scale test. This was slightly longer than the expected value using the fire-resistance calculations provided in the standard. However, the standard uses a conservative char rate. Based upon the data presented, it appears that the failure times in the intermediate-scale test were close to full-scale failure times, or perhaps slightly longer. Furthermore, the test was able to differentiate between different face lamination adhesives. Future development and refinement of the intermediate-scale test would require matched materials tested at full and intermediate scales.

Literature Cited

APA. 2017. ANSI/APA PRG 320. Standard for performance rated cross-laminated timber. Tacoma, WA: APA — The Engineered Wood Association.

ASTM. 2014. ASTM E119. Standard test methods for fire tests of building and construction materials. West Conshohocken, PA: American Society for Testing and Materials.

ASTM. 2016. ASTM D6815-09. Standard specification for evaluation of duration of load and creep effects of wood and wood-based products. West Conshohocken, PA: American Society for Testing and Materials.

CSA Group. 2006. CSA O177-06. Qualification code for manufacturers of structural glued-laminated timber. Toronto, Ontario, Canada: CSA Group.

CSA Group. 2019. CSA O86-19. Engineering design in wood. Toronto, Ontario, Canada: CSA Group.

Miyamoto, B.; Bechle, N.J.; Rammer, D.R.; Zelinka, S.L. 2021. A small-scale test to examine heat delamination in cross laminated timber (CLT). Forests. 12(2): 232. DOI: 10.3390/f12020232.

Rammer, D.R.; Zelinka, S.L.; Hasburgh, L.E.; Craft, S.T. 2018. Ability of finger-jointed lumber to maintain load at elevated temperatures. Wood and Fiber Science. 50: 44-54.

Schaffer, E.L. 1968. A simplified test for adhesive behavior in wood sections exposed to fire. Research Note FPL-0175. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

Su, J.; Lafrance, P.-S.; Hoehler, M.; Bundy, M. 2018. Fire safety challenges of tall wood buildings – Phase 2: Task 2 & 3 Cross Laminated Timber Compartment Fire Tests. Quincy, MA: Fire Protection Research Foundation.

ULC. 2004. CAN/ULC S101-04. Standard methods of fire endurance tests of building construction and materials. Scarborough, Ontario, Canada: Underwriters Laboratories of Canada.

WWPA. 2007. Fast facts: heat-resistant adhesives (HRA) and finger-jointed lumber. 0204/FF-HRA/5-07/150. Portland, OR: Western Wood Products Association. 2 p.

Yeh, B.; Herzog, B.; Ipsen, P.; Brooks, R. 2005. Adhesive performance at elevated temperatures for engineered wood products. In: Proceedings of the International Conference on Wood Adhesives, San Diego, CA: 195-201.

Zelinka, S.L.; Pei, S.; Bechle, N.; Sullivan, K.; Ottum, N.; Rammer, D.R.; Hasburgh, L.E. 2018. Performance of wood adhesives for cross laminated timber under elevated temperature. Paper MAT-O1-04. Proceedings of the World Conference of Timber Engineering, Seoul, Republic of Korea.