WCTE 2018
2018 World Conference on Timber Engineering
August 20 - 23, 2018 | Seoul, Republic of Korea

PERFORMANCE OF WOOD ADHESIVES FOR CROSS LAMINATED TIMBER UNDER ELEVATED TEMPERATURE

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ABSTRACT: The increasing use of cross laminated timber (CLT) panels in large multi-story buildings has highlighted the structural performance of CLT in fire as a critical issue concerning life safety and serviceability. It is well-known that wood material strength decreases when exposed to elevated temperature for an extended period of time. For CLT panels, another level of complexity lies in the mechanical properties of the glued interface under high temperature. In this study, the tensile strength of typical North American wood species and shear strength of the glued interface of commonly used adhesives in CLT production were evaluated at different levels of elevated temperatures. The researchers systematically tested glue interface and wood samples in a controlled temperature chamber and obtained the load-deformation curves of the specimens until failure was observed. A total of five temperature levels were tested, with three wood species and four wood adhesive types. The glued interface strength was also compared to wood material strength itself under different temperatures. For each test, multiple samples were tested to ensure statistical significance of the results. The ultimate objective of this study is to develop a mechanistic model for CLT panels that can take into account the effect of temperature. In this paper, only the design, execution, and results from the elevated temperature tests are presented.

KEYWORDS: elevated temperature, fire performance, wood adhesive, cross laminated timber, mechanical strength

1 INTRODUCTION

With the increased availability of cross laminated timber (CLT), large scale multi-story mass timber buildings have become a viable alternative to steel and concrete construction in commercial and mixed-use applications in the United States. However, mass timber buildings are currently still governed by the same height and area restrictions as light-framed wood construction in the U.S., despite their increased fire resistance. With the increasing demand from building occupants and architects for exposed natural wood finish on the interior (e.g. large area of ceiling as exposed wood in a modern mass timber building shown in Figure 1), fire performance of CLT and other mass timber products is of great importance in the evolution of future building codes. A better understanding of the fire dynamics and material performance of mass timber and especially CLT are needed to demonstrate its performance for potential for use above six storeys.

Figure 1: *Example of a modern mass timber building with large area of exposed CLT*

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With the help of special performance-based permitting, only a handful of tall (greater than six stories) mass timber buildings have been constructed in North America. One reason for this is that current prescriptive provisions do not permit these buildings under the height and area limitations set forth in the International Building Code (IBC). The International Code Council (ICC), which publishes the IBC, established an *Ad Hoc* committee to study the issue of tall wood buildings and potential, future prescriptive provisions permitting tall wood buildings in the IBC.

In a previous research assessment, understanding the fire dynamics in compartments constructed with combustible materials was identified as one of the biggest research needs to achieve fire-safe, tall wood structures. In the research assessment, Gerard et al. [1] noted that in certain cases, a "second flashover" has been observed in wood structures. In general, second flashover occurs when passive fire protection falls off exposing a fresh, pre-heated surface of wood which ignites and causes the heat release rate to rise [2]. In CLT structures, a second flashover can occur when unburned wood is exposed to hot gasses within the compartment if the gypsum wallboard fails, if there is char fall-off from the CLT, or if there is delamination of a layer from the CLT. While both char fall-off and delamination involve a portion of the charred CLT falling off and exposing a fresh surface, delamination is a term that is applied specifically to failures that occur at the interlaminate interface [2, 3]. Delamination has been highlighted as an important research need as certain adhesives can fail before the char temperature of wood [4-12]. In a recent large scale compartment fire test program led by USDA Forest Products Laboratory (FPL), compartment fire behaviour of CLT buildings was studied under different levels of gypsum wall board protection (see Figure 2). The delamination of exposed CLT walls and ceilings were observed (Figure 2), which is related to the deterioration of adhesive layer strength under high temperature [13]. It is worth noting that although delamination was observed in the tests, there was no secondary flashover because the delamination occurred when the compartment had cooled down.

While the char-rate of wood has been well studied, a complete understanding of the performance of the adhesives in engineered wood is still lacking. The performance of wood adhesives under high temperature and fire scenarios has been studied since the 1960's in seminal work by Schaffer [14]. Schaffer placed wood bond-lines under a burner and afterwards 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 char layer and the fire front moved through these adhesives similarly to solid wood. It is generally recognized that the char front moves through phenolic based adhesives the same way it moves through solid wood and these adhesives behave similarly to solid wood under fire[15][16]. 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 [4]. However, with the more robust workability requirement for CLT panel manufacturing, more and more manufactures are using polyurethane adhesives for CLT production both in Europe and North America. Polyurethane adhesives are easier to work with, but have been shown to break down at temperatures below the char temperature [5, 17]. Premature delamination (delaminated wood was not fully charred) can add significant fuel load to the compartment and also expose fresh wood surface for fire consumption. For this reason, predicting the performance of CLT under fire requires detailed knowledge of wood strength and adhesive strength over a wide range of temperatures including that below the char temperature. Currently, there are very limited data on CLT and its adhesive's structural performance under elevated temperatures. This study was conducted to develop a small scale testing procedure for wood material and adhesives under different temperatures. The data from the tests can be used to study premature delamination potential and the impact of temperature gradient (caused by fire) on the strength and stiffness of CLT panels in bending.

Figure 2: *Full scale compartment fire test on CLT building conducted in 2017 by FPL (top) and example of a delaminated surface (bottom)*

2 METHODOLOGY

The main objective of this study is to develop a temperature-sensitive mechanistic model for CLT panel wood material as well as the glue line interface. Firstly, elevated temperature tests on wood material and glued joints were conducted to gather data on their strength and stiffness values as functions of temperature. Then, this temperature-sensitive model can be included into a layered mechanistic model of composite engineered wood product model (e.g. CLT panel) to extrapolate large scale member performance under various temperature gradients. The size effect of small scale testing and heat transfer modeling need to be considered in this process. In this paper, only the results from the small scale material testing under different temperatures are presented and discussed.

The experiments were conducted at Forest Products Laboratory, in Madison, WI, over the summer of 2017 and consisted of two main categories. The first was a variation of ASTM D143 – Tension parallel to grain [18]. The tensile specimens were produced out of three wood species groups commonly used in CLT production in North America, namely Spruce Pine Fir (SPF), Southern Yellow Pine (SYP), and Douglas Fir (DF). Five temperature levels were considered in the tensile test, namely 25°C, 100°C, 140°C, 180°C, and 220°C.

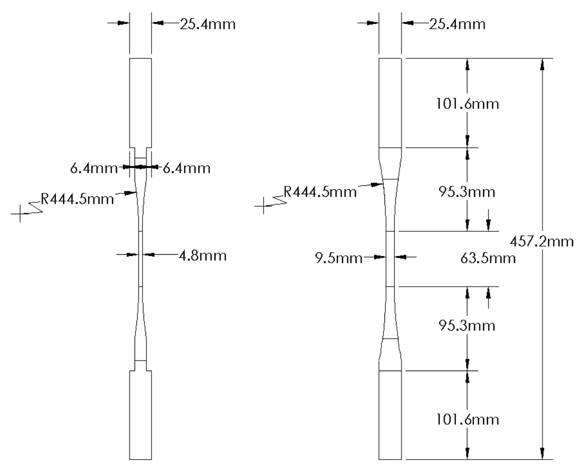
The shear tests involved a custom made specimen with half-lap joint glue-connected together. Only one wood species was used (Douglas fir). The shear test also included a baseline case of wood material in shear with a specimen geometry identical to that of the half-lap glue joint comprised of solid wood. The specimens for the baseline case have the same shape and cuts as the glued specimens, but the half-lap joint was not cut apart. A total of four glue types were tested including two types of polyurethane (PUR-1 and PUR-2), one type of phenol-resorcinol-formaldehyde (PRF), and one type of melamine-formaldehyde (MF) adhesives. The shear test was conducted at 5 elevated temperatures: 100°C, 140°C, 180°C, 220°C, and 260°C. These elevated temperatures were chosen because they are lower than the wood char temperature of 288^{o}C and would represent the scenario of delamination that could result in second flashover. Room temperature tests were not conducted because these adhesives were known to be equivalent to wood strength under room temperature. The specimens were prepared with the adhesive manufacturer specified pressure and time. Gluing was performed within 3 hours of the samples being surfaced. The PURs and PRF adhesives were tested 2.5 months after gluing. The MF was tested approximately 2.5 weeks after being removed from the press. The geometries of the specimens are shown in Figure 3 for both tension and shear tests. In order to account for variability in the individual specimen material and workmanship, at least 10 replicates were tested for each condition. The total number of specimens tested was approximately 400. All the conditions tested are shown in Table 1.

3 TEST PROCEDURE

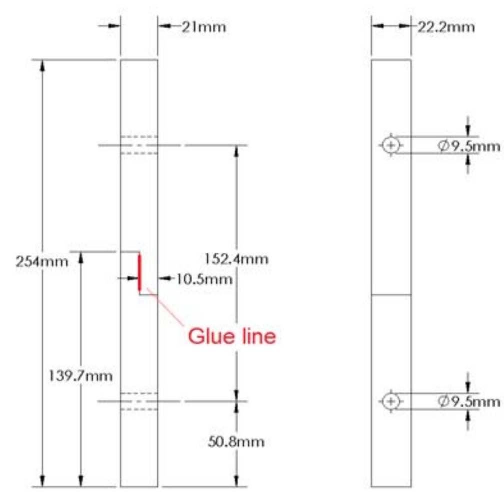
Figure 4 shows photos of the test specimen and equipment. The test specimens were placed in an Instron testing frame and subjected to a quasistatic loading condition at a constant displacement rate. Gripping devices for the Instron system reached through insulated openings at the top and bottom of a special BEMCO temperature controlled oven such that the entire specimen was inside the oven for the duration of an experiment. In order to save testing time, all heated specimens were preheated to 100°C in separate oven (preheating took approximately 15 minutes). Additional heating was applied in the testing oven after the specimen was installed until the desired temperature was reached at which point the loading test began.

Table 1: **List of specimen conditions tested**

Tensile Tests				
DF	SPF	SYP		
25, 100, 140, 180, 220 C^{o}				
Shear Tests				
Wood	PUR-1	PUR-2	PRF	MF
100, 140, 180, 220, 240 C^{o}				



Tensile Specimen



Shear Specimen

Figure 3: *Geometry of the small scale test specimen*

Two thermocouples were placed in the specimens to monitor the temperature. An Instron load cell measured the load and Istra4D from Dantec Dynamics recorded images for digital image correlation analysis through post-processing to obtain displacement and strain. The image correlation measurement was necessary for two reasons. Firstly, a suitable physical displacement sensor was not available to the lab under high temperature. Secondly, the shear strain for the glue line is difficult to extract from traditional measurements. Figure 5 illustrates an example of the displacement and strain fields for a shear specimen from the image correlation process. For tensile tests under 200°C, an Instron extensometer was also installed to record strain near the testing section of the specimens

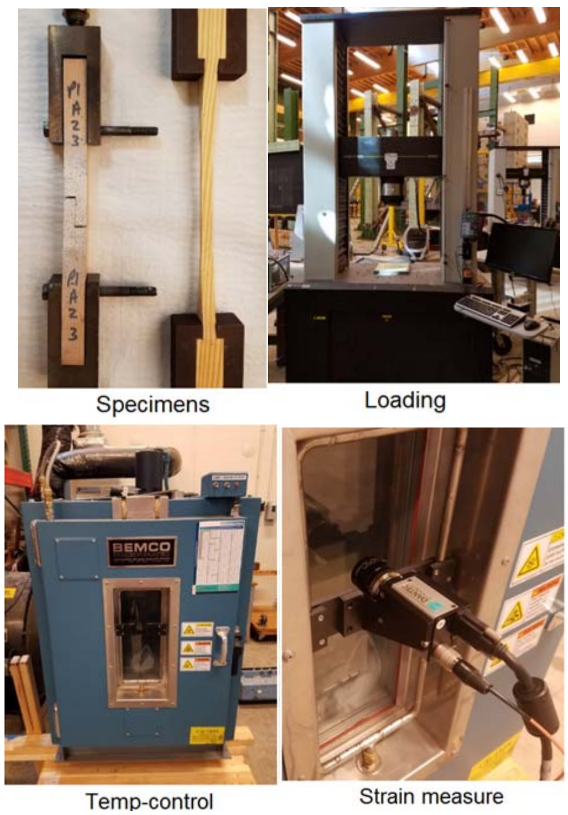


Figure 4: *Instrumentation and equipment used in the tests*

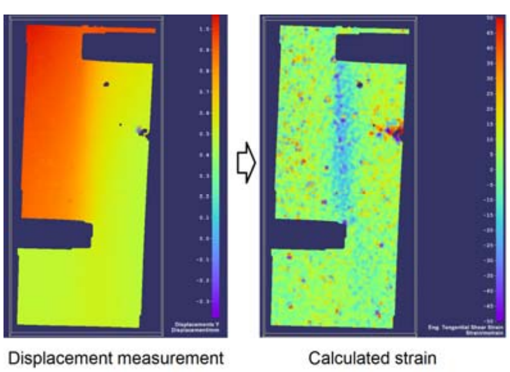


Figure 5: *Example of shear specimen displacement and strain captured using image correlation.*

4 TEST RESULTS

The wood specimens were tested to failure in tension. All specimens failed within the gauge length at the narrow section in the middle. The nominal failure stress (strength) was calculated by dividing the maximum tensile force by the initial cross-sectional area and shown in Figure 6.

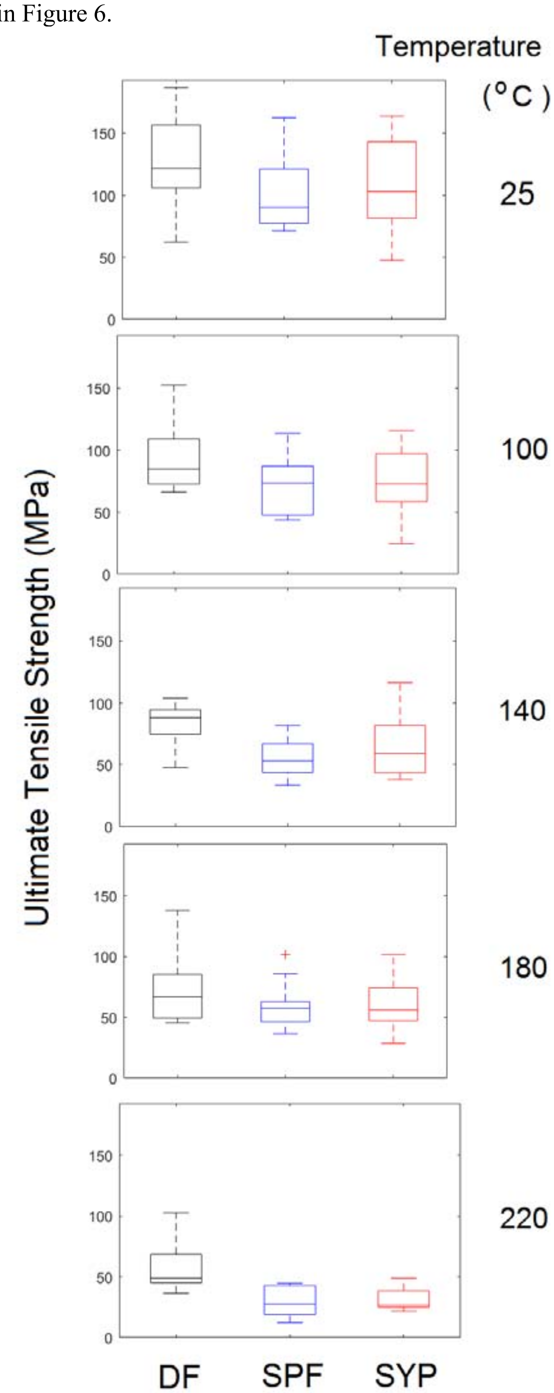


Figure 6: *Wood tensile specimen strength results at different temperatures*

The tensile strength of the wood material decreases in an approximately linear fashion with respect to an increase in temperature (Figure 8). The variability of the strength also decreases with an increase in temperature. The relative strength among tested wood species relateive to each other remains the same.

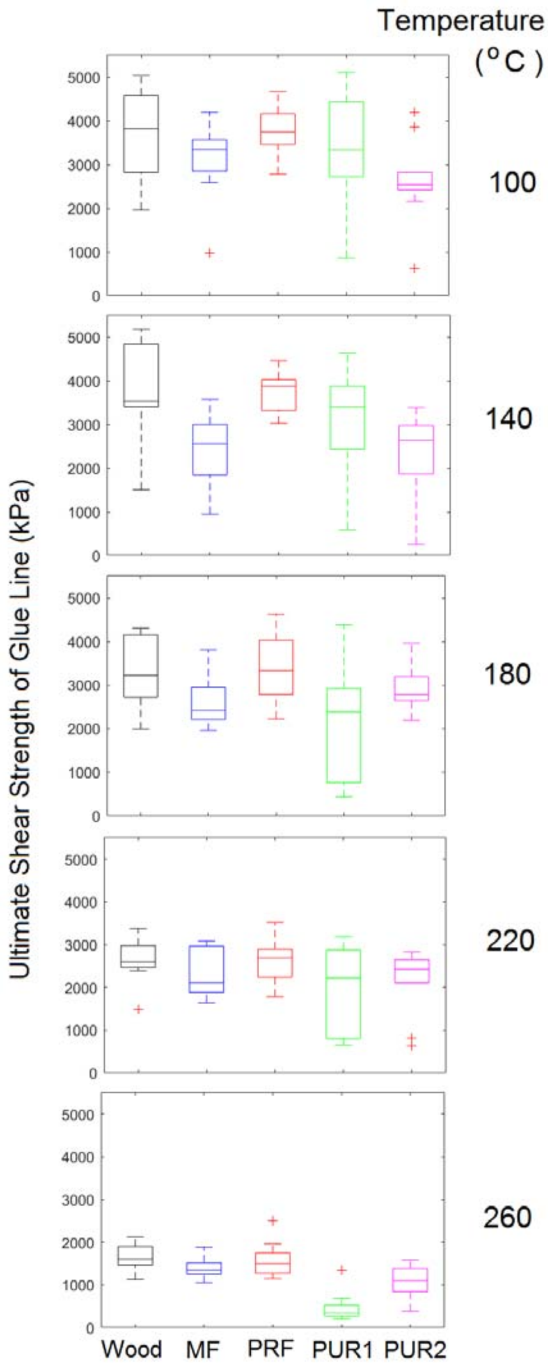


Figure 7: *Glue line shear specimen strength results at different temperatures.*

Similarly, Figure 7 presents a plot of strength vs. temperature for the shear specimen. It should be noted that under lower temperatures, some specimens did not necessarily break at the glue line.

Figure 8 summarizes the trends of the average tensile and shear strength deterioration under elevated temperature. The results indicate that the strength of all tested adhesives deteriorates with an increase in temperature, with some differences between glue types. The PRF glue performed very close to the solid wood material at all temperatures, while other glue types were shown to be weaker. The strength degradation is not linear with respect to temperature increase. The shear strength decreases at a faster rate with respect to temperature than that of tension. This trend is similar for all shear specimens.

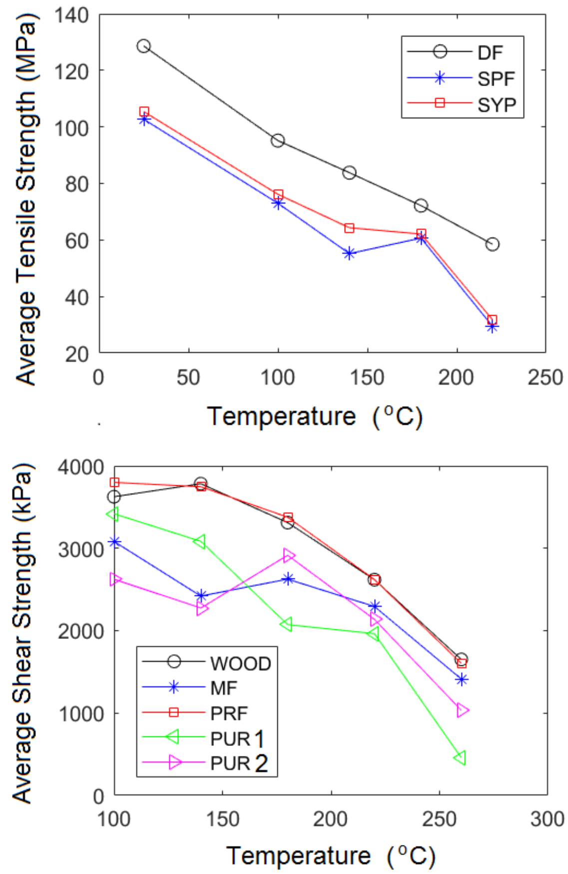


Figure 8: *Trends of strength variation as function of temperature.*

5 CONCLUSIONS

This paper presents results from a comprehensive testing program focused on mechanical properties of wood material and glue types typically used for CLT production in North America under elevated temperatures. PUR1 and PUR2 are the most commonly used adhesive formulations for CLT production in North America. The test results showed that the strength and stiffness of wood and glue joints change with temperature and the sensitivity of different glue and wood types to temperature is different. This test program is the first part of a larger study aiming at understanding CLT panel structural performance under elevated temperature. From the current test data, it is possible to develop a temperature sensitive model for glue connections in shear and wood material in tension. While the implication of the observed test results on different wood and glue types will need to be evaluated through additional modelling and testing, it is hopeful that small scale tests as proposed in this study will be able to inform and correlate to large scale engineered wood products performance under elevated temperature.

ACKNOWLEDGEMENT

This study was funded by the U.S. Endowment for Forestry and Communities. This financial support is greatly appreciated.

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In: WCTE 2018, 2018 World Conference on Timber Engineering, Korean Institute of Forest Science, Seoul, Republic of Korea; 2018