COMPARING TIMBER ADHESIVE SHEAR STRENGTH PROPERTIES AFTER FIRE DAMAGE

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ABSTRACT

Due to the rapid growth of the engineered timber industry worldwide, a deeper knowledge of the high temperature material properties and behaviour in fire is required. The primary difference between mass timber and engineered timber is the addition of an adhesive through which several laminates of timber are built up into larger sections. Adhesives may degrade at lower temperatures than timber which can lead to delamination during or after a fire. In order to fully understand the performance of engineered timber materials after extreme heating, it is necessary to study the behaviour of these adhesive layers during in-fire and post-fire exposure, the latter being the primary focus of this paper. Current standards do not look at the performance of wood adhesives beneath the char layer in burned engineered timber, but previous tests have shown that this may introduce complex failure mechanisms. To study this issue, samples with two different types of adhesives were heated with various incident heat flux exposures and heating durations followed by mechanical shear testing. A cone calorimeter was used for controlled heating exposure, and the residual shear strength of the glue lines was measured through an innovative mechanical apparatus. Digital image correlation technology was used to assess the deformation (slip) of the adhesive layer as load was applied. It was found that the residual shear strengths were highly variable but did show a slight correlation with the heating duration. Additionally, the slip measurements of the shear line showed that generally, the unheated adhesives were more ductile than the heated samples which exhibited brittle failure.

INTRODUCTION

Undoubtedly, the use of engineered timber has greatly increased over the past decade, with societal drives for sustainable and aesthetic buildings, research advancements and building code amendments. Such buildings are beginning to use massive engineered timber elements such as glued laminated timber (Glulam) and cross-laminated timber (CLT). This is primarily driven through sustainability measures as mass timber takes time to grow, whereas timber used in engineered cases can be harvested earlier and quickly re-grown. Currently, numerous timber building are planned or being constructed, with several competing for the title of tallest wood building in the world. Recently, the University of British Columbia constructed a wood residence building which took the lead with 18 storeys, but this will not remain the tallest as other projects have already been proposed, approved and begun constructed.

Currently, the methods for evaluating the fire performance of exposed engineered timber can be analogous to that of solid massive timber, in which a sacrificial char method is employed. Using previously calibrated charring rates, the cross-sectional area loss of wood over the desired fire resistance period could be estimated for un-encapsulated timber. That char depth thickness is then added to the minimum required cross-sectional area to resist the structural loading during a fire. This method works quite well as a means of fire protection of exposed wood structural elements (negating spread effects), but does not consider a holistic understanding of the composite material behaviour. The introduction of adhesive bonds into the wood section may have a complex influence on the performance of engineered timber, and may differ from

solid wood in elevated heat exposures as lower temperatures may have an effect on the polymeric resin materials. The topic of the effects of different adhesives in fire-damaged engineered wood products materials has been identified as needing research by a colloquium of international material experts at the National Institute of Standards and Technology fire safety roadmap workshop [1]. This study begins to serve this discussion with reference to Glulam and its typical adhesives.

BACKGROUND

As a relatively nascent material that is rapidly increasing in use and function, engineered timber performance must be understood in detail. This entails a thorough understanding of the effects of adhesive and how it differs from solid-sawn lumber.

Engineered Timber Adhesives

Timber adhesives have been under development for several decades, with improving properties as science has gained understanding in optimizing polymer properties – they are however, like any polymer, very complex and require detailed consideration when one wishes to analyse their in-fire performance [2]. Currently, there are numerous types of adhesives available to laminated timber manufacturers. This study is focused on two of the most commonly used adhesives at present, polyurethane and resorcinol resins. Polyurethane, commonly abbreviated to PUR, is a newer adhesive which is beginning to see industry wide usage as it becomes more economical [3]. The second adhesive, resorcinol, is a phenol-formaldehyde formulation commonly referred to as PRF. This adhesive has been used in manufacturing wood bonds in several applications for decades. In this study, the PUR samples were bonded by a Glulam manufacturer with a proprietary adhesive, while the PRF samples were prepared by the authors on site.

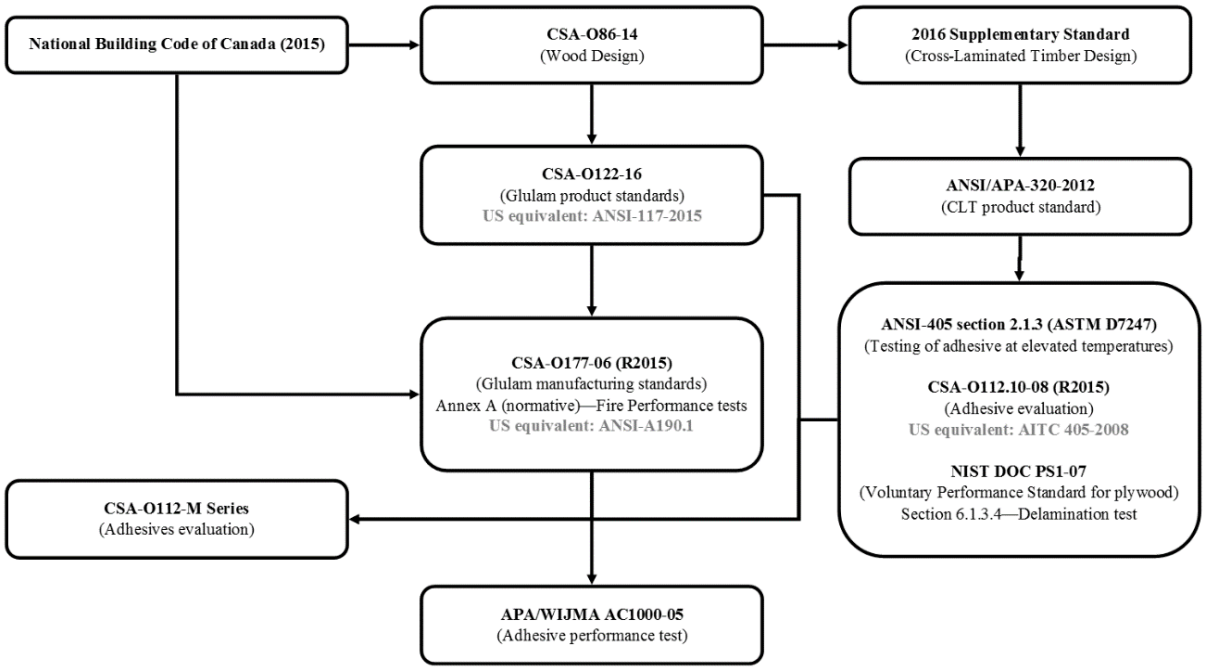
Standards on Adhesives Performance at Elevated Temperatures

In standards, the consensus is that the adhesive should be of higher strength than the timber itself, so that the material strength properties can be based on those of the wood. This allows easy access to the practitioner in the design of engineered wood, which is largely akin to the design of solid-sawn lumber, with some different modification factors. Like in all material designs, these factors adjust material strength for an acceptable probability of failure, accounting for uncertainties in the product manufacturing.

As there are many different types of engineered wood products available and numerous types of adhesives, several different adhesive standards exist in Canada and internationally. In the authors' opinion, the standards are somewhat disjointed, and many refer to different high-temperature tests and acceptance criteria. Standards exist for adhesives on their own and for the combination of wood and adhesives, and may take the form of a product standard or a manufacturing standard. An outline of some of the standards concerning timber adhesives at elevated temperatures are shown in Figure 1.

The Canadian wood design standard CSA-O86 currently references to the Glulam product and manufacturer standards [4]. These, in turn, cite the CSA-O112-M series of standards for the evaluation of timber adhesives which was originally developed in the late 1970s [5]. The series gives an overview of test procedures in O112.0, and then defines acceptance criteria for several different types of adhesives in O112.1-8 (O112.7 referring to PRF). O112.9 [6] and O112.10 [7] are newer standards which were developed to provide manufacturers with the ability to use newer adhesives not included in the earlier series, after the Canadian federal government funded a wood research initiative [3]. The main test method for evaluating the strength of adhesives in this series is a shear test by compression loading, with specimens that are 50 mm squared by 40 mm thick, with a slight offset on either side of the shear plane. This test is akin to the ASTM D905 test for evaluating the shear strength of adhesives [8].

Figure 1: Overview of Standards in Canada related to Timber Adhesives at Elevated Temperatures



The 2016 Supplementary Standard for CSA-O86 will give added guidance for cross-laminated timber (CLT), and points to ANSI/APA-320 for increased adhesive standards [9]. This document gives provisions for Canadian adhesives to meet ASTM D7247 through ANSI-405 [10]. The ASTM D7247 standard test is meant to evaluate the shear strength of adhesives at elevated temperatures [11], using an almost identical test specimen as in the CSA-O112-M series and ASTM D905. The test procedure involves heating several specimen sets of bonded and solid control samples to a bondline temperature of 220°C for a specified duration of time which depends on the product. Following the heating, the residual shear strength ratio for the bonded specimens must be at least equivalent to the lower 95% confidence interval for the results of the solid wood control specimens. ANSI/APA-320 also specifies that Canadian adhesives must meet section 6.1.3.4 of the NIST Voluntary Performance Standard DOC PS1 [12]. This test uses a Bunsen Burner flame exposure on a sloped surface of the specimen where several glue lines are exposed. After the test, the degree of delamination of the glue lines is visually inspected.

CSA-O177, the "Qualification Code for Manufacturers of Structural Glued-Laminated Timber" gives extra requirements for adhesives meeting CSA-O112.9 [13]. Adhesives following this standard for evaluation of structural wood adhesives for exterior exposures must follow additional tests outlined in normative Annex A of the standard. In this section, a manufacturer has two options of test paths. In the first method, the products must pass a small scale flame test akin to the DOC PS1 Bunsen Burner test, to assess delamination and glue line opening. Additionally, the products must pass APA/WIJMA AC1000, which was the first standard test meant to assess the performance of adhesives at a temperature near the ignition point of wood [14]. It uses the same test procedure as ASTM D7247, which was originally published one year after APA/WIJMA AC1000. As of yet, the authors are not aware of any standard tests that evaluate the performance of adhesive beneath the char layer in burnt engineered timber. Alternatively, in lieu of these two tests, the manufacturer may perform a full-scale fire test in conformance with CAN/ULC S101 to prove adequate fire performance. Adhesives meeting CSA-O112.7 (PRF) inherently meet bondline fire performance requirements.

MOTIVATION

As aforementioned, with the use of engineered timber rapidly increasing globally –even in the un-encapsulated condition, it is important to increase the data available with respect to every aspect of such materials and their behaviour during and after heat exposure. The primary difference between engineered timber and solid massive timber is the introduction of adhesive lines within the structural section. Previous tests by the authors have shown that this introduction may have a complex effect on the failure mechanisms of these materials after an extreme heating event [15]. Moreover, the adhesive standard tests that have been thoroughly conducted by labs and manufacturers do not test the effect of fire on the adhesive below the char layer. As the previous tests suggested that the adhesive within the internal unheated wood zone may have been affected, the goal here is to study that effect in detail. A deeper understanding of the adhesive contribution to the behaviour of engineered timber, specifically Glulam, after fire damage is of importance.

METHODOLOGY

In order to achieve the objective of this research study, to investigate the behaviour of Glulam adhesives beneath the char layer, a test programme was developed in which numerous samples of Glulam adhesive lines were tested under various conditions.

Specimen Preparation

Specimens were prepared in the lab from Glulam products made of spruce-pine-fir species, primarily of Black Spruce, which is the most commonly used species group available in Canada. Glulam blocks were prepared with a thickness of one laminate (40 mm), and with an area of 100 mm by 100 mm. The specimens used differed from the standard shear test specimens used in CSA-O112 to fit in the cone calorimeter apparatus. The blocks were cut from the larger Glulam billets, ensuring that an adhesive line was located along the centreline of the sample for shear testing. The majority of samples were cut around manufacturer made glue lines which used a PUR adhesive, and additionally limited samples with lab-prepared PRF adhesive lines were produced.

Cone Calorimeter Heating

A cone calorimeter was used as a heat source with a constant incident heat flux. Samples were wrapped in aluminium foil to concentrate the heating to the top surface, and were placed in holders with insulation beneath the specimen. The tests done are listed in Table 1 and Table 2.

Table 1: Incident Heat Flux and Heating Duration of PUR adhesive samples

Heat Flux (kW/m^2)	-	50	50	50	50	30	30	30	30
Heating Duration (mins)	-	3	6	10	15	3	6	10	15
Number of Samples	2	2	2	2	2	2	2	2	2

Table 2: Incident Heat Flux and Heating Duration of PRF adhesive samples

Heat Flux (kW/m^2)	-	50	50	50	30	30	30
Heating Duration (mins)	-	3	6	10	3	6	10
Number of Samples	1	2	2	2	1	1	1

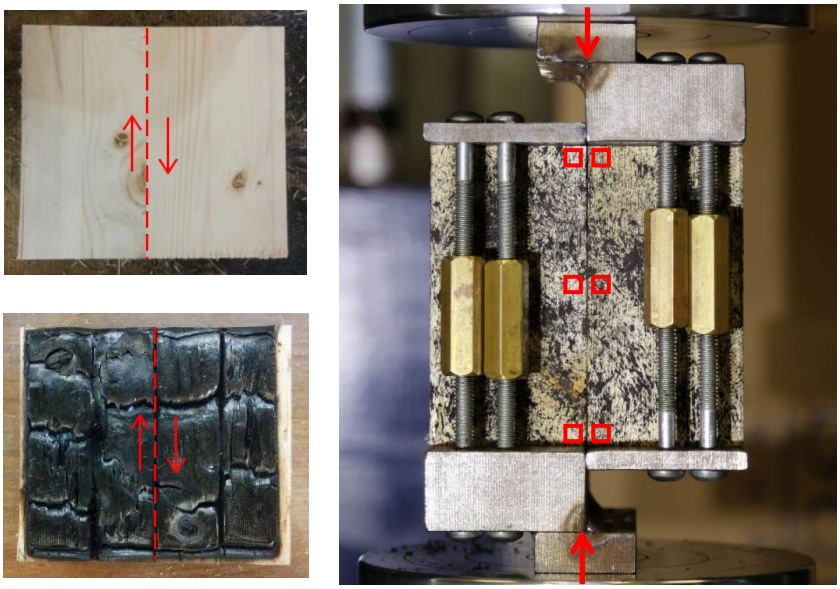
An incident heat flux of 50 kW/m^2 was chosen as a typical heat exposure [16] and 30 kW/m^2 was chosen as a comparative heat flux exposure. Exposure times were limited to three, six, ten and fifteen minute durations to observe the varying performance of the remaining adhesive with different quantifiable charring depths. Two samples from the PUR set and one sample from the PRF set were left unheated as control specimens.

This testing procedure also differs from some of the standard tests with regards to the heating, as many standards for evaluating adhesives at elevated temperatures specify a target bondline temperature which must be sustained throughout heating. They are typically done in an oven, where the entire specimen sees uniform heating, and they are tested while still at the elevated temperature. For the purposes of the study, one-sided extreme exposure was used to actually char the wood and leave an unheated wood and adhesive region below the pyrolysis zone. Additionally, tests were done once the specimens had been cooled to mimic the previous tests.

Shear Test Apparatus

A novel shear test apparatus was modified from previous shear analyses of concrete [17], to create a setup compatible with the sample dimension requirements for the cone calorimeter. This non-standard test method was used because the testing objective was to perform an exact comparative basis of the remaining shear capacity of several different samples tested under the same setup.

Figure 2: Shear plane shown on unheated and heated samples (left) and shear apparatus test setup (right)



Digital Image Correlation

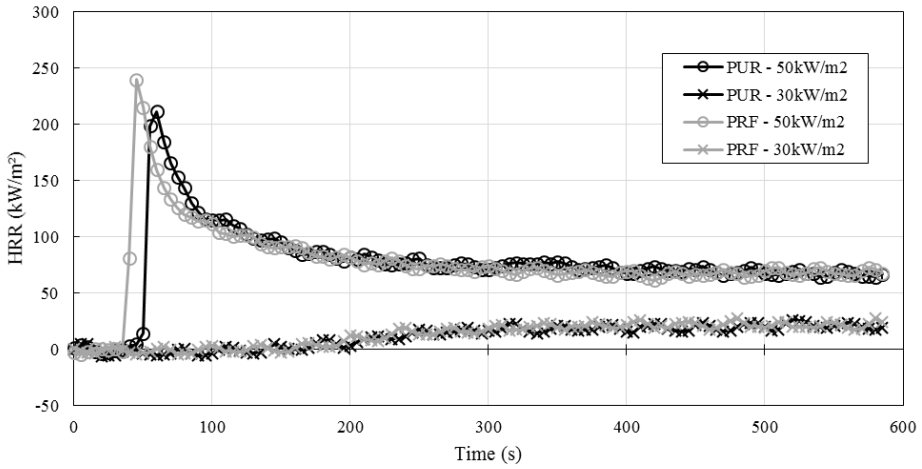
Digital Image Correlation (DIC) was used to monitor the deformations of the specimens as they were tested in shear. This is a relatively nascent technique, which was previously proven accurate for measuring displacements and strain in wood specimens [18,15]. The accuracy of the program has been quoted as 0.1 pixels [19], and a past study comparing the accuracy of the DIC measured strains to a bonded 60 mm strain gauge on wood determined an accuracy of about 0.15 pixels [20]. The technique commonly uses a validated pixel-tracking software, GeoPIV8, to locate user-specified locations on a series of high-resolution photographs. In these tests, the slip was measured at 3 points along the shear line: at the top, middle and bottom of the specimens. A sample of the pixel patches used to track the slip are shown in the right-hand image in Figure 2.

RESULTS AND DISCUSSION

Each of the heated samples were exposed to a constant heat flux of 30 kW/m^2 or 50 kW/m^2 in the cone calorimeter for the durations listed in Table 1 and Table 2. No spark was used to ignite the specimens,

but rather they were allowed to self-ignite to be more representative of reality in real construction. Sample heat release rate (HRR) curves of four samples are shown in Figure 3.

Figure 3: Sample heat release rate curves for samples with 10 minute heating duration

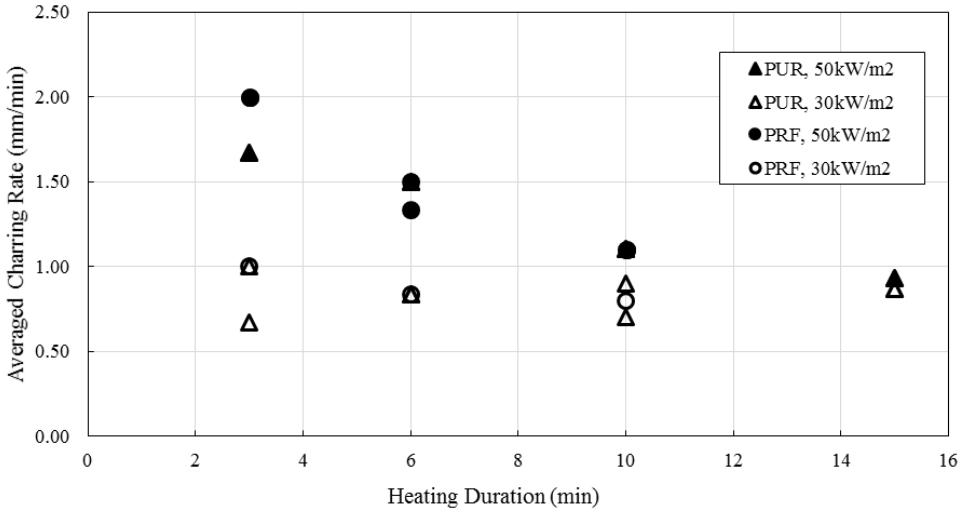


In the 50 kW/m^2 tests, the specimens ignited at an average of 34 seconds after heat exposure began. Divided into adhesive types, PUR ignited around 37 seconds on average, while the average time that PRF samples began flaming was at around 30 seconds. This behaviour can be seen in the trends in Figure 3 above, where the 50 kW/m^2 PRF sample reaches its peak HRR before that of PUR. This can be attributed to the fact that the PRF adhesive used had a much lower flash point than the PUR adhesive - 67°C versus 93°C, respectively as quoted by the manufactures. This indicates that the PRF adhesive may give off sufficient vapours to ignite at a lower temperature than the PUR.

In the 30 kW/m^2 tests, typically the specimens did not ignite at all. Smouldering was seen on the test specimens after about 3 minutes of heat exposure. On the PUR specimens that were tested at 30 kW/m^2 for 15 minutes, flaming was seen after about 7-7.5 minutes of heat exposure. However, the 10 minute samples did not ignite.

Average charring rates over the total heating duration for each sample were computed and are plotted in Figure 4 below versus their respective heating duration.

Figure 4: Averaged charring rates versus heating duration of all test specimens



This plot shows a negative correlation between the averaged charring rates and the heating duration, indicating that the charring rates slow down as the heating time increases. This is to be expected as the timber begins to char and build up a protective insulating layer to protect the inner wood and slow the char rate. The values appear to be approaching the recommended value of 0.7 mm/min as the heating duration increases. Additionally, 50 kW/m^2 can be seen as a more severe heat exposure than the standard fire for which the code charring rates are calibrated. The cone test utilises incident heat exposure, whereas a standard fire test would compensate for the heat exposure being emitted thereby reducing the incident heat exposure as timber can give off heat.

It has also been observed that the charring rates on smaller specimens are more severe than on larger specimens, likely due to larger thermal inertia [15]. The 30 kW/m^2 samples do not show a decrease in charring rate with time possibly because they do not build up a sufficient char layer to protect the inner wood, however the charring rates are smaller with the lower incident heat flux and only smouldering fire.

The peak loads of each specimen compared to heating duration were also examined and can be seen in Figure 5 and Figure 6.

Figure 5: Peak loads versus heating duration for PUR test specimens

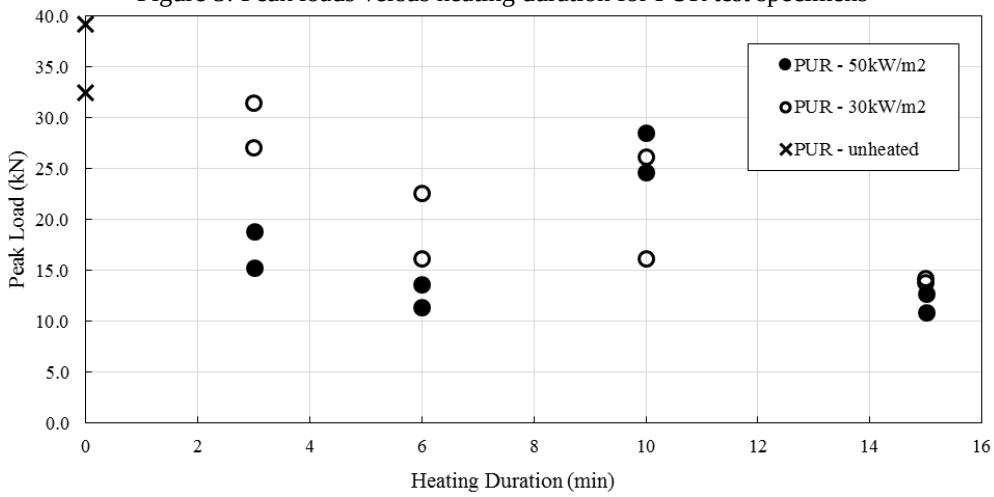
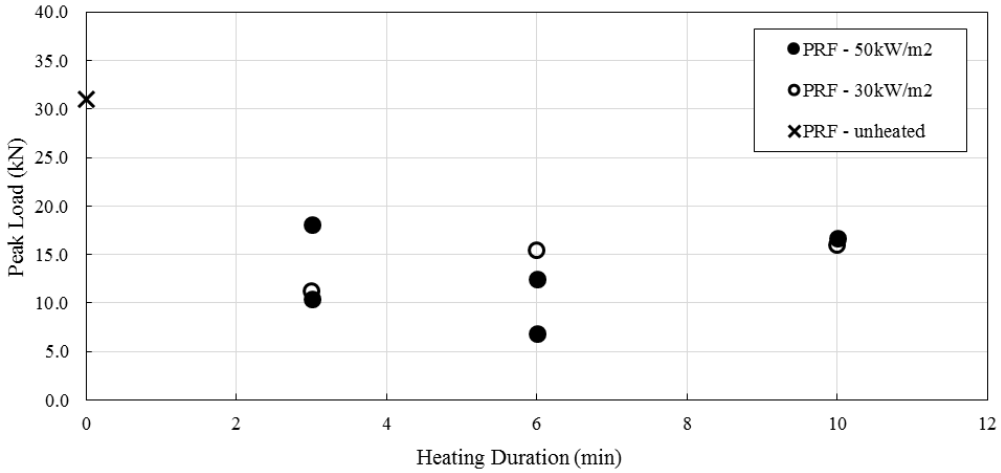


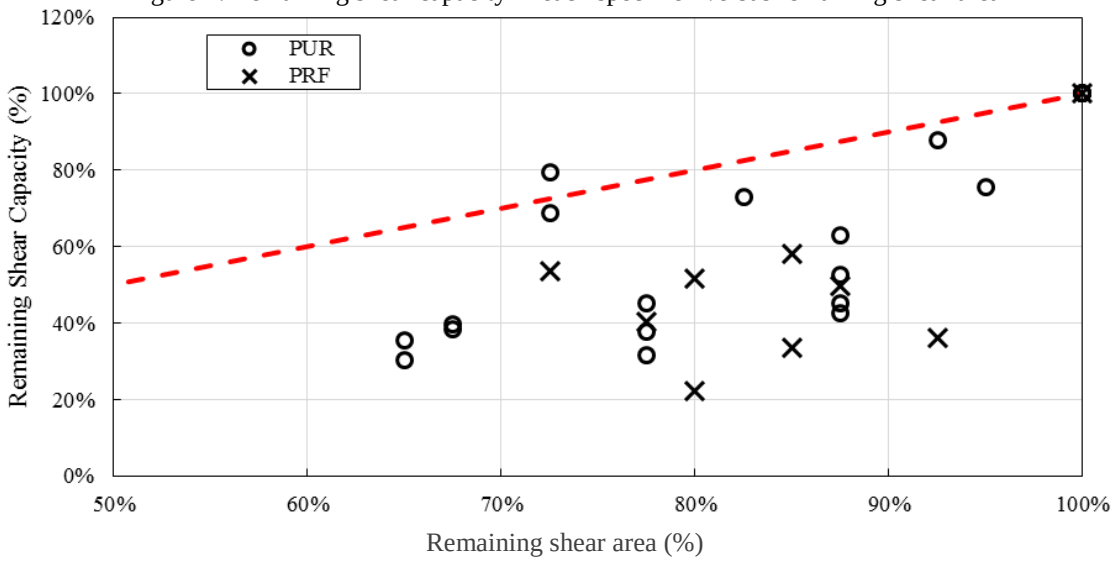
Figure 6: Peak loads versus heating duration for PRF test specimens



As can be seen in the above figures, the peak loads for all of the specimens were highly variable. In both cases, there appears to be several outliers at the 10 minute heat duration in an otherwise linear trend correlating loss of strength to heating duration and therefore loss of cross-section. The peak loads in Figure 6 for the PRF samples seem to have had a greater loss of strength than the samples in the PUR plot (Figure 5). It is important to note that the PRF samples were the ones with adhesive bonds prepared in the lab, not by the manufacturer. In these samples, glue lines could be considered thicker as craftsmanship was not equivalent to a factory produced bondline, however this craftsmanship used can be considered of typical research practice particularly for proprietary engineered timber system manufacture. This highlights the importance of manufacturing standards and good detailing on engineered wood products, to be used in structural applications and in lab testing which may be used to inform standards.

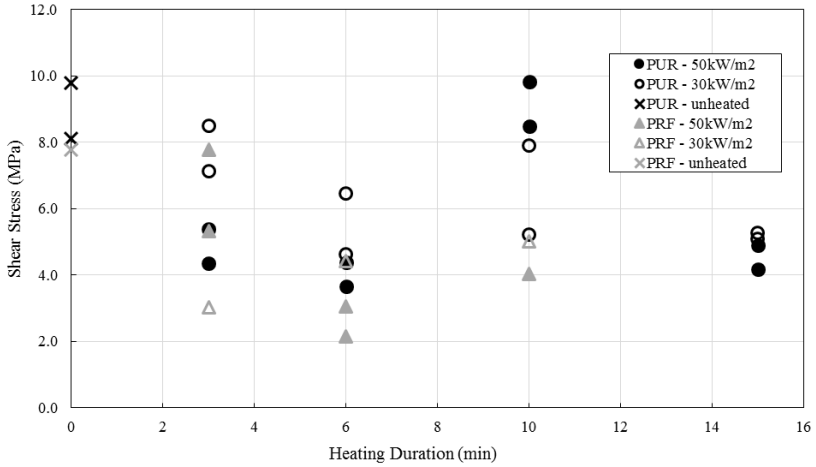
The residual shear capacity for each specimen was compared to the control specimen shear capacity (the average of the two samples for PUR) to get a percentage of remaining shear capacity in each sample. This was then compared to the remaining shear area based off of the char depth measured at the centreline of each specimen. The results are plotted in Figure 7, where the red dashed line represents a perfect correlation between the residual shear capacity ratio and the remaining shear area, should sacrificial char layers be considered wholly accurate and not account for adhesive degradation. The reader is cautioned however to consider the size of the samples tested when interpreting Figure 8 for application. The plot demonstrates that the typical specimen lost more shear strength than expected compared to the reduction in area.

Figure 7: Remaining shear capacity in each specimen versus remaining shear area



The shear stresses in the specimens were also calculated using the peak load recorded over the reduced shear area beneath the char depth. Figure 7, shows that the shear stresses experienced by the unharmed adhesive layers were again highly variable, although char depths increased almost linearly with heating duration. This indicates that the adhesive may be affected by temperatures within the unheated wood region that are too low to degrade the wood itself. This phenomenon is typically what is studied in standard adhesive evaluation tests in which the specimens are heated to temperatures below the wood pyrolysis temperature range.

Figure 8: Shear stress of all samples versus heating duration



The slip between the two shear surfaces at failure was measured for several samples using the Digital Image Correlation technique. The PRF unheated sample had an average slip of 0.20 mm at failure. One of the unheated PUR samples had an average slip of 0.29 mm, and one had a slip of 0.09 mm. The latter is close to the average failure slips of the heated samples, which had a mean value of 0.10 mm and a standard deviation of 0.05 mm. Sample plots of slip versus load comparing heated and unheated samples of PRF and PUR are shown in Figure 9 and Figure 10.

Figure 9: Sample slip versus load trends for two PUR samples

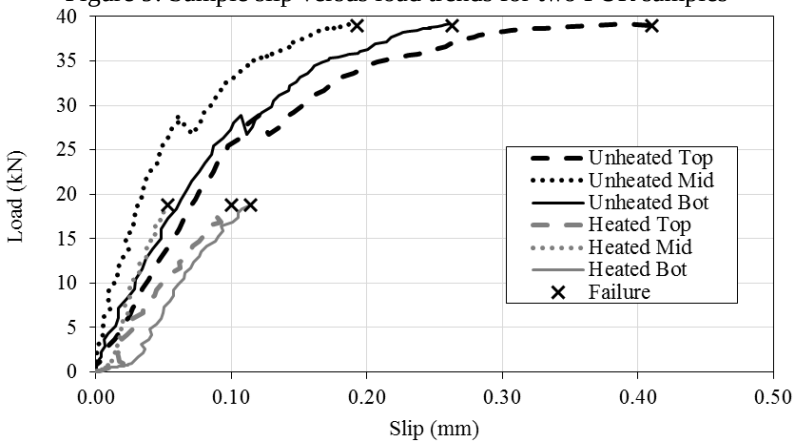
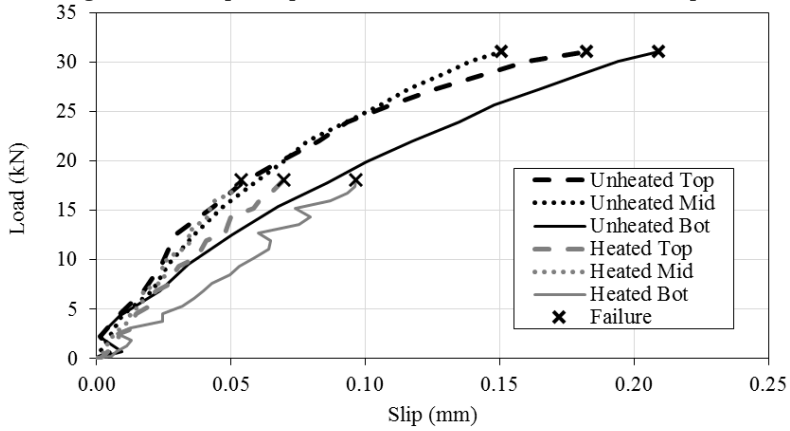


Figure 10: Sample slip versus load trends for two PRF samples



The trends show that the heated samples are follow similar trends to the unheated samples, however they exhibit a more brittle adhesive failure. This could be due to adhesive damage from the elevated temperatures as resins cannot typically be melted and reformed like some other polymers, but rather they degrade. This behavior could explain the reduction in residual shear stress seen in Figure 7.

However, it is important to note that the slip data collected is quite sensitive to error when dealing with such small displacements. As aforementioned, the previously determined error in DIC on wood specimens was 0.15 pixels. For these test images 0.15 pixels corresponds to about 0.0065 mm. Additionally, it is expected that there is some sensitivity to other errors in the measurements [18]. The authors suggest that the values reported be considered over 92.5% accurate when these issues were taken into account (user error for example).

PRELIMINARY CONCLUSIONS AND FUTURE WORK

The primary goal of this study was to investigate into the performance of adhesives in burnt Glulam specimens, specifically the glue lines beneath the pyrolysis zone. In the sacrificial char method, this wood is assumed to be unaffected by the extreme heating. In previous tests involving Glulam, however, it was suggested that the presence of these adhesives after heating introduces a more complex behaviour of the specimen that is not fully captured in this methodology [15]. The test results indicate that the residual strength of the adhesives are quite variable on such small-scale samples when actual pyrolysis of the timber is involved. Future replica tests would be useful in determining the extent of such variability and what uncertainties are involved. The tests do indicate, however, that the adhesive beneath the char layer is somewhat affected by the heating exposure as the shear stresses varied and the specimens exhibited a more brittle behaviour. This is in line with previous tests in which the behaviour of some burned Glulam samples indicated a higher stiffness and slightly lower strength than their unburned counterparts.

These preliminary results demonstrate the importance of investigating the behaviour of the adhesives within the unheated wood regions of burnt samples of engineered timber. Such sporadic results also indicate that more tests are required to be done, and show the importance of quality in professionally prepared engineered timber adhesive bonds. It is important to note once again that the specimens used in this study were very small compared to Glulam structural members which would be used in the modern high-rise timber buildings being proposed. Such members could have cross-sectional dimensions upwards of half a metre, and would not lose nearly as much strength as the unheated region would be much larger with higher reserve strength. If we are to continue innovating with wood and using it as a sustainable alternative building material, we must ensure that the complexities of engineered timber in fire are wholly understood.

ACKNOWLEDGEMENTS

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