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Bench-scale fire tests of Dark Red Meranti and Spruce finger joints in tension

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Abstract

This study investigates the secondary failure of Malaysian Dark Red Meranti (*Shorea* spp.) and Spruce (*Picea abies*) finger joints in a glulam beam in a fire test using a bench-scale test set-up. Secondary failure is the occurrence of failure of the bond lines due to fire and the falling off of the outermost tension layers, exposing the uncharred inner layers to a sudden increase of fire intensity. The lack of published work and the difficulties in describing the behaviour of the finger joints after the secondary failure in a full-scale fire test has identified the need for a simple bench-scale method, incorporating the conditions of the standard fire test. This paper focusses on the performance of the finger joints which together with other defects such as knots and splits are generally the weakest component in the glulam beam. The finger joints were bonded with structural adhesives, specifically phenol resorcinol formaldehyde (PRF) and polyurethane (PUR). They were tested in tension to imitate the failure of finger joints on the tension side of a standard fire test of a

glulam beam. Constant heat flux was introduced to the finger-jointed specimens to replicate the secondary failure of a glulam beam in the standard fire test. The results of this study indicate a relationship between the charring rate and density of the specimens, with higher density Dark Red Meranti showing lower charring rate compared to the lower density Spruce specimens. Factors such as constant heat flux as opposed to the time-increasing heat flux exposure and specimen size influenced the charring rate of the specimens. The char rate was measured at the early stages of the fire test, which is known to have higher values since the build-up of the charred layers was not sufficiently substantial to protect the inner unburnt wood. Overall, the bench-scale fire test set-up was able to differentiate the fire performance of the adhesives, with PRF showing better fire performance compared to the specimens finger-jointed with PUR adhesive. In addition, tensile tests at ambient temperature showed no significant difference in tensile strength between finger joints bonded with different adhesives for the same wood species. The tensile strengths of the finger joints bonded with different adhesives were influenced by the temperature profile through the joint. The proposed bench-scale fire test was used to compare the quality of the adhesives in a fire situation, specifically with respect to secondary failure. The PRF was selected as the reference adhesive.

Keywords:

Dark Red Meranti (*Shorea* spp.), Spruce (*Picea abies*), finger joints, bench-scale fire test, charring rate, secondary failure, heat flux, tensile strength, phenol resorcinol formaldehyde and polyurethane adhesive.

1. Introduction

It is beneficial to improve the understanding of the behaviour of glue-laminated timber (glulam) when exposed to fire because any additional information related to fire performance will significantly improve fire safety design. Generally, glulam beams are tested in bending in a standard fire resistance test [1], where the outermost tension lamella experiences the highest stress and at the same time is suddenly exposed to fire [2]. The charred outermost lamella will lose its strength and relatively reduce the effective cross-section of the beam. This will increase the deflection of the beam and the tensile stress at the interface between the residual beam and the failed outermost lamella. Consequently, secondary failure may occur where the outermost lamella starts to delaminate and fall off from the beam. This will lead to increased fire intensity and charring rate on the uncharred inner lamellae because of the sudden exposure to fire when the outermost charred lamella no longer acts as a thermal insulator. At present, there is a lack of published work which describes the behaviour of finger joints following secondary failure incidents. In a standard fire test, it is extremely difficult to evaluate the conditions of finger joints because of the limited access and control of the material once the test starts and secondary failure occurs.

It is also well known that large-scale standard fire tests for glulam beams are time-consuming, expensive to set up and may not describe adequately the fire performance of the tested materials [3,4]. Attempts were made to introduce small-scale or bench-scale tests to investigate the performance of adhesives in finger joints and bonding lines at elevated temperature and in fire conditions. Craft et al. [3] reviewed some of the small-scale test methods available and proposed a new method to improve the shortcomings of the previous tests. The authors described the

advantages of their small-scale test method, which simultaneously evaluates multiple finger-jointed specimens under tension in an oven. However, their method does not describe the behaviour of finger joints at secondary failure since it uses a relatively low temperature and longer set-up time (approximately 30 minutes for temperature recovery in the oven) rather than the sudden exposure to high temperature which occurs when the char layer falls away. Klippel et al. [4] conducted extensive tests on small-scale finger joints at elevated temperatures using 12 different adhesives. The results showed moderate decrease in tensile strength of the joints in relation to the testing temperature of between 20 to 140^{o}C. For temperature up to 220^{o}C, phenol resorcinol formaldehyde and melamine urea formaldehyde showed mostly wood failure indicating the wood itself was being tested rather than the adhesives. These tensile bench-scale tests must be further refined before they can be used as an alternative to full-scale fire tests but none describe the behaviour of finger joints in a secondary failure incident.

Tensile testing was used in this study to imitate the behaviour of the finger joints at the outermost tension lamella of a glulam beam which experiences the highest stress in a bending test in a standard fire test. Frangi et al. [5] performed tensile and bending tests to evaluate the performance of finger joints bonded with different adhesives at elevated temperature. They concluded that tensile tests were suitable for evaluating the influence of adhesives in finger joints when tested at elevated temperature but did not report any significant correlation between adhesive types and strength in bending.

Generally, the fire performance of timber structures can be described by the charring rate of the wood. The charring rate is subsequently influenced by factors including the material properties, namely density, moisture content, chemical composition and

permeability, and test conditions particularly thermal exposure, scale/size effect and direction of burning [6,7]. In this paper, the influence of factors such as density, constant heat flux exposure and size effect on the charring rate of the specimens tested using a bench-scale fire test are described. This paper aims to analyse the fire performance of hardwood finger joints in tension when exposed to a constant heat flux from a bench-scale set-up. The objective is to observe the behaviour of the finger joints in the tension region when exposed to sudden high temperature which occurs following the secondary failure of the glulam beam in a standard fire test.

2. Materials and method

2.1 Finger joints preparation

Kiln-dried Dark Red Meranti (*Shorea* spp.) and Spruce (*Picea abies*) were used in this study. The average density of Dark Red Meranti (DRM) and Spruce was (659 ± 99) kg/m^3 and (462 ± 92) kg/m^3 with the average moisture content of 14 and 12% respectively. The wood pieces were conditioned in a conditioning room at a temperature of 20^{o}C and relative humidity of 65% before the cutting of the finger profiles.

Larger DRM and Spruce pieces with the cross-section of 51 x 99 mm and 44 x 115 mm respectively were used to create the finger-jointed specimens. Timber pieces with little or no defects were chosen to minimise their influence on the results. Finger profiles with length and pitch of 15 and 3.8 mm respectively, were cut from these pieces using a manual feed finger cutter. The length and pitch of the finger joints satisfied the requirements of the standard EN 14080 [8]. They were later pressure bonded with structural adhesives, namely phenol resorcinol formaldehyde (PRF) and

polyurethane (PUR) adhesives respectively. These finger-jointed pieces were then left to cure for two weeks, allowing them to reach their optimum strength. They were then cut and ripped to the test specimen size of 10 x 42 x 300 mm with the finger joints located in the middle (Fig. 1). A total of 84 finger-jointed specimens were produced for different types of test conditions (Table 1). The test specimens were kept in the conditioning room prior to being tested, to minimise any changes in moisture content.

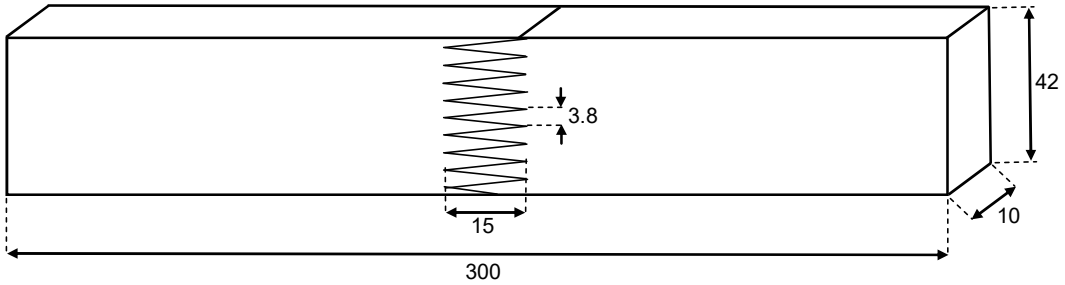

Fig. 1. Specimen and finger joints dimensions in mm

Table 1: Test conditions

Test conditions	Species	Adhesives	Quantity
Tensile test in fire	DRM	PRF	10
		PUR	10
	Spruce	PRF	10
		PUR	10
Tensile test at ambient temperature	DRM	PRF	10
		PUR	10
	Spruce	PRF	10
		PUR	10
Specimens with thermocouples	DRM	PRF	1
		PUR	1
	Spruce	PRF	1
		PUR	1
		Total	84

2.2 Bench-scale fire tests

The preparation of specimens for the bench-scale fire tests is shown in Fig. 2. The ends of the specimens were reinforced with plywood and holes were made for anchoring purposes. These reinforcements were made to prevent failures at the gripping sections. Stone wool was used to protect both faces of the specimen against heat exposure, allowing the exposure of the specimen edge from one direction only. A load of 2.5 kN was introduced at the start of the test. This load was determined based on the load ratio of 14% (Spruce) and 8% (DRM) of the ultimate load of the reference finger-jointed specimens tested in tension at ambient temperature. The 2.5 kN load was used for both species so that comparison can be made between the fire performance of the Spruce and DRM. Furthermore, the aim was to differentiate the time to failure of the adhesives by extending the time of the test when using smaller load values. A constant heat flux of 50 kW/m^2 was introduced at the start of the test. Prior to the tests, a heat flux gauge was used for calibration. Previous tests exposed with 50 kW/m^2 incident radiant heat flux [9] have led to a charring depth of approximately 40 mm in one hour, which matches with the charring depth expected in standard fire resistance tests. The heat flux of 50 kW/m^2 was also found to correspond well with the ISO 834 and EN 1363-1 standard time-temperature curve for the first 30 to 40 minutes of the fire resistance tests [10-12].

Fig. 2. Specimen preparation for fire tests a) DRM without end reinforcement and b) Spruce with end reinforcement

The specimen together with the protective stone wool was held together with a steel casing for ease of placing them directly under the cone heater (Fig. 3). Additional stone wool was used to protect the outer region of the specimen near each end, thus exposing only the top edge of the specimen in the inner area of the casing where the finger joints were located. The reinforced ends of the specimen were clamped to steel tabs with a bolt passing through each hole (Fig. 3b). One end was anchored to the wall and the other end was connected to dead weights using a simple pulley system (Fig. 3c). Prior to the start of the test, fibre glass wool was used to protect the specimen. The fibre glass wool was removed at the same time as the application of load and the test began with the recording of time. It was pertinent to immediately start the fire test once the specimen was put under the cone heater because of the possibility that the specimen might start to heat up due to the elevated temperature in the surrounding region. The layout of this test attempts to imitate the conditions of secondary failure as described in the earlier section, where the finger joints were

exposed to a sudden heat flux once the fibre glass wool was removed and the load was applied.

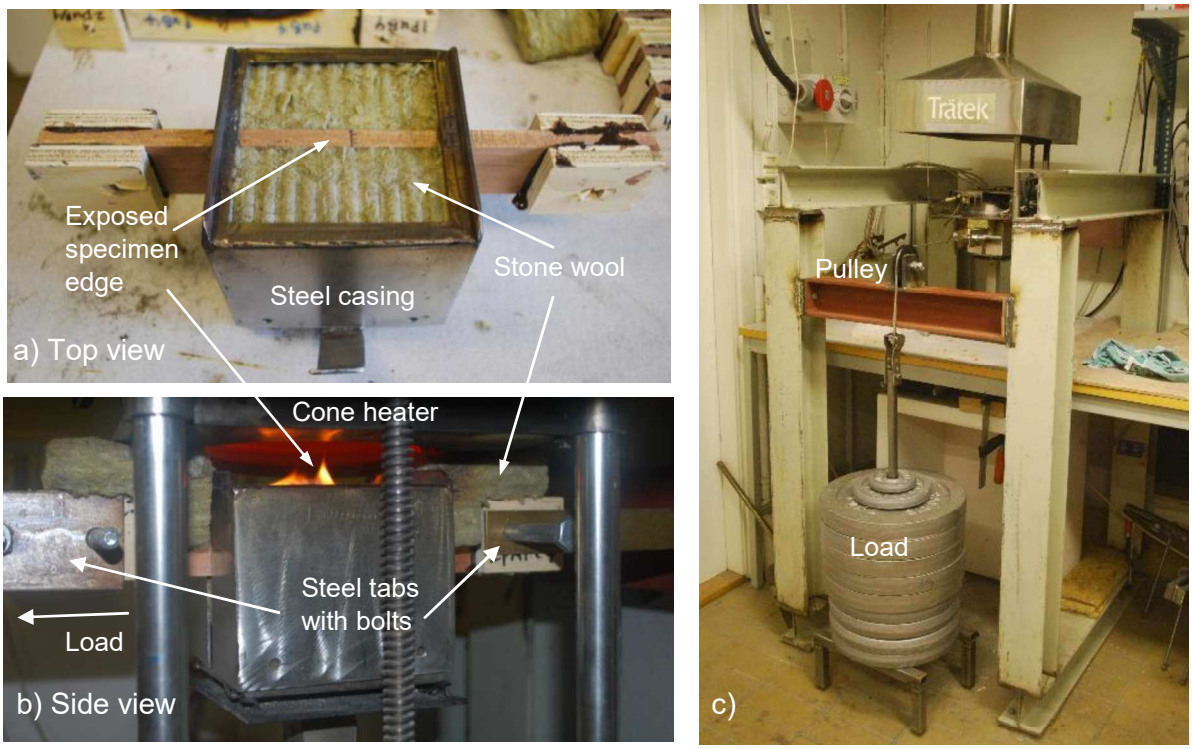

Fig. 3. Bench-scale fire test set-up (a) specimen held within steel casing, (b) specimen under the cone heater, (c) general view with load applied

Immediately after the failure of the specimen, it was quickly removed and soaked in water to remove the remaining embers, preventing further charring once the test was completed. The charred area was brushed off and the residual depth was measured. The one dimensional charring rate (β) was calculated based on the ratio of the charred depth to the measured time to failure. The residual cross-section was measured which includes an estimation of the rounded area of the charred line. The residual tensile strength was calculated based on the ratio of the applied load (2.5 kN) to the measured residual cross-section after the fire test. The ignition time of the

specimen was recorded and the time to reach failure for this bench-scale fire test was approximately 5 to 11 minutes.

Four specimens of different species and adhesives (Table 1) were prepared and each was instrumented with eight thermocouples. The thermocouples used in this study were 1.5 mm in diameter, glass fibre insulated Type K and were connected to a datalogger. They were positioned horizontally, laid parallel to the isotherm. The purpose of this test was to measure the temperature profile through the specimen at different depths, with no load applied during the fire test. The first thermocouple (T1) was located at 5 mm from the exposed surface. The subsequent thermocouples (T2 to T8) were positioned every 5 mm across the depth of the specimen (Fig. 4). Holes with 1.5 mm diameter were drilled into the middle of the specimen (5 mm from the specimen's surface) and staggered along the depth. The tips of the thermocouples were inserted into the holes to measure the internal temperature of the specimen.

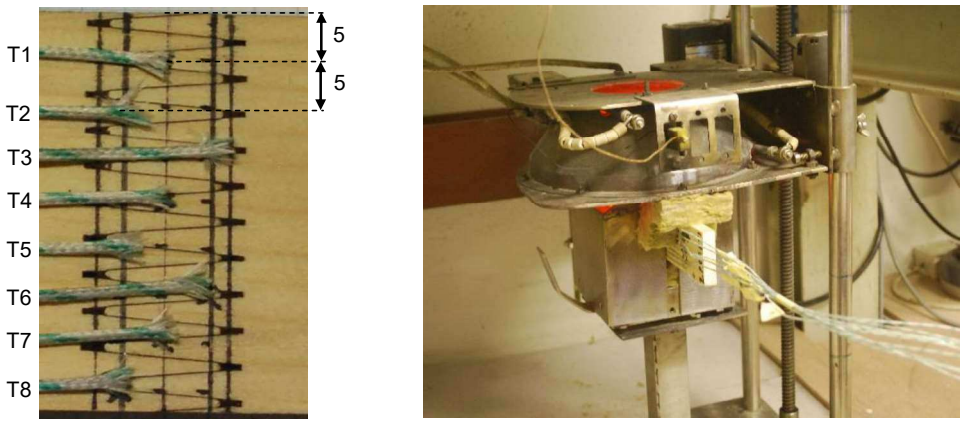

Fig. 4. Specimens with thermocouples attachment (measurements in mm)

2.3 Tensile tests at ambient temperature

The tensile tests at ambient temperature were conducted to obtain reference values for the tensile tests in the fire condition. They were conducted using an Alwetron universal testing machine with a maximum load of 50 kN. A cross-head movement of approximately 5 mm/min was applied and the test specimens failed between 2 to 4 minutes. The specimen was gripped with a steel clamp at each end, occupying approximately 80 mm of the specimen's length at both ends. The finger joints were positioned in the middle of the set-up and the specimen was properly aligned with the clamp, minimising bending when applying tensile load. The tensile strength, f_t was calculated based on the ratio of the maximum load, F_{max} to the cross-sectional area, A of the specimen:

$$f_t = F_{max}/A \quad (1)$$

3. Results and discussion

In general, the specimens finger-jointed with polyurethane (PUR) retained a higher residual cross-section when compared to the phenol resorcinol formaldehyde (PRF) specimens for both DRM and Spruce wood species. The typical failures of the specimens in the bench-scale fire test are shown in Fig. 5. Almost all of the specimens exhibited failure along the joints (Fig. 5a). Some specimens showed fingers failure (Fig. 5b) and mixture of joints and wood failure (Fig. 5c). Few of the specimens exhibited failures near defects and along the slope of the grain (Fig. 5d). The failure along the joints indicates that the adhesives had a significant influence in the fire performance of the finger joints. An additional feature of failure was wood rupture indicating that the glue lines of the finger joints across a partial section of the

specimen (e.g. Fig. 5d) had higher tensile strength than the solid wood when tested in fire condition [13].

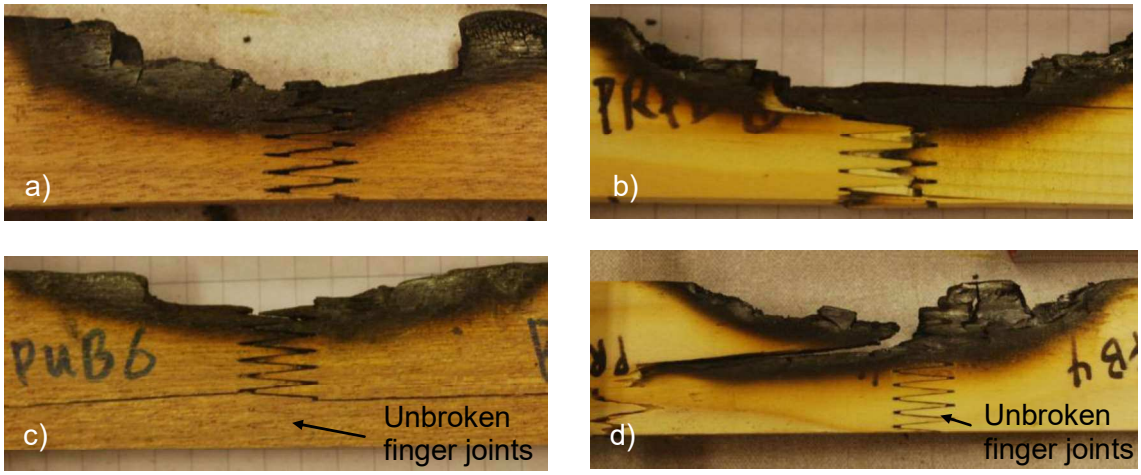

Fig. 5. Typical failures of finger-jointed specimens a) failure along the joints; b) failure of the fingers; c) mixture of joints and wood failure; d) wood failure

3.1 Fire performance of finger joints with different adhesives

The average results of the bench-scale fire tests are shown in Table 2. As expected, the fire performance of the PRF were better than the PUR adhesive. For finger joints glued with PUR, the average time to failure (TTF) was 72% (Spruce) and 57% (DRM) of the time measured for failure of specimens glued with PRF. The specimens bonded with PRF exhibited higher average residual strengths compared to the PUR for both DRM (33%) and Spruce (20%), as result of the lower values of residual cross-section (A_r) of PRF compared to the specimens glued with PUR adhesive. The results indicated that the finger-jointed specimens bonded with PRF have better fire performance compared to the specimens glued with PUR. The

distribution of the residual tensile strength values with density of the specimens jointed with PRF and PUR are shown in Fig. 6.

Table 2: Overview of fire test results

Species	Adhesives		Time to failure, TTF (min)	Residual cross-section, A_r (mm^2)	Charring rate, β (mm/min)	Ignition time (min)	Residual tensile strength (MPa)
Spruce	PRF	Average	7.59	258.8 (61*)	2.03	0.37	9.70
		SD	1.18	17.26	0.19	0.08	0.58
Spruce	PUR	Average	5.47	310.3 (73)	1.99	0.38	8.10
		SD	0.98	22.21	0.26	0.16	0.60
DRM	PRF	Average	11.0	244.2 (58)	1.61	0.48	10.3
		SD	2.31	10.11	0.37	0.19	0.41
DRM	PUR	Average	6.24	330.3 (76)	1.50	0.47	7.72
		SD	0.89	13.65	0.09	0.14	0.31

*Ratio to the original cross-section (in percentage)

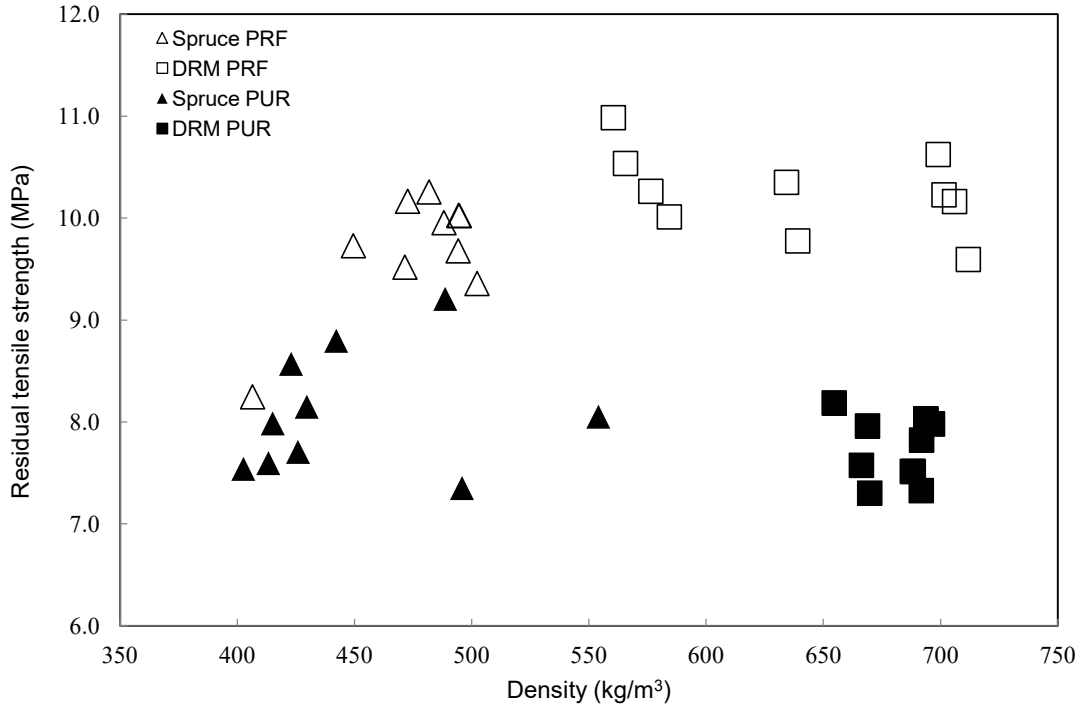

Fig. 6. Residual tensile strength of finger-jointed specimens of DRM and Spruce as a function of density

The PUR adhesive in this study may not be fully cross-linked and so might be expected to fail viscoelastically at elevated temperature. Thus, the PUR adhesive may be at a disadvantage compared to the highly cross-linked PRF adhesive. These results agree well with some other reports indicating that PRF adhesives have better fire performance than PUR adhesives. König et al. [14] reported that the moment resistance of three lamellae glulam beams, with the finger joints bonded with PUR in the middle region of the tension side, was 70 to 80% of the beams with PRF finger joints when tested in fire. However, this comparison does not mean that all PUR adhesive systems are inadequate in providing sufficient strength for the production of structural finger joints. Klippel et al. [4] stated that in a large-scale fire test, structural finger joints bonded with PRF may not always show better fire performance than

finger joints bonded with PUR adhesives. In their study, one of the PUR adhesives used in the elevated temperature tensile tests showed results comparable to the PRF adhesives. The PUR adhesives can be specially formulated to resist high temperature load with higher cross-link density and hard urea segments.

3.2 Factors affecting the charring rates

The charring rates of DRM for both PRF and PUR bonded finger joints were lower than the Spruce specimens (Fig. 7). These results were expected since DRM specimens have higher density compared to Spruce. Nevertheless, it can also be seen in the figure that several DRM specimens with lower density have high charring rates similar to the Spruce specimens. Overall, a one-way analysis of variance (ANOVA) test showed a statistically significant difference at 95% confidence level for charring rate values between Spruce and DRM specimens. Fig. 7 also shows a trend of increasing charring rate with decrease in density of the specimens. Higher wood density exhibits lower charring rate as reported in many previous studies [15-17]. Meanwhile, for the same wood species, comparison of charring rate between specimens finger-jointed with different adhesives, namely PRF and PUR, showed no significant difference at 95% confidence level when tested statistically with the ANOVA test. This analysis signified that the different adhesives used in the bonding of the finger joints do not influence the charring rate in this bench-scale fire test. This can be explained by the fact that the bonding area of the finger joints was small in comparison to the overall cross-section of the specimen.

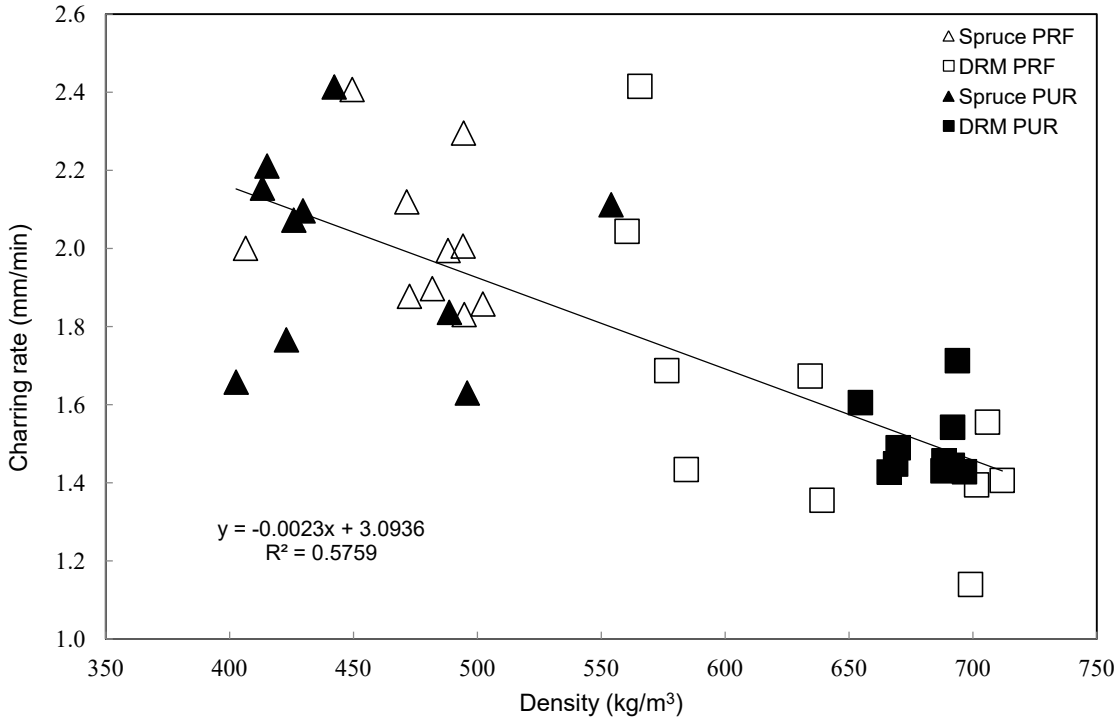

Fig. 7. Charring rates of finger-jointed specimens as a function of density

The measured charring rate values in this study were higher compared to the notional charring rate and one-dimensional charring rate published in EN 1995-1-2 [18]. Although in reality the charring rate is nonlinear, the published values are taken to be constant with time in simplified design methods [7]. In fact, the charring rate was found to be higher initially and decreased when the charred layer started to build up. The charred layer becomes the insulation layer and protects the inner unburnt wood and the charring later stabilises to a constant rate. Majamaa (1991) (cited by Friquin, p.317, [6]) stated that different specimen thicknesses require different time periods for the charring to achieve a constant rate. He mentioned that a specimen with thickness of 40 mm may require a period of 10 minutes for the charring to reach a constant rate while 30 minutes was needed for specimens of 80 mm thickness. In this study, the nominal thickness of the specimens was 42 mm and the average time

to failure ranged from 5 to 11 minutes. The charring rate values in this study were measured in the early stages of fire. There was insufficient built-up of charred layer to insulate the unburnt inner wood of the specimens, thus higher charring rate values were measured.

The constant heat flux used in this study may contribute to high charring rates compared to using a time-increasing heat flux [19]. Similarly, the method in this study was structured to imitate the condition of secondary failure in fire where the inner lamellae were exposed to the sudden constant heat flux.

Another factor influencing the values of the charring rate is the size of the specimens. The specimens used in this study were small compared to the standard fire test of glulam beams. As noted in the earlier section, the objective for studying this bench-scale fire test was to replicate the full-scale standard fire test with a simpler and faster method, thus the use of small-sized specimen is a prerequisite. Frangi & Fontana [20] concluded that the charring rate of the underside of timber beams when exposed to fire on three sides would increase when its residual cross-section decreases below a certain minimum values. They suggested that the constant charring rate in the simplified calculation method of fire resistance for structural members should only be used if the residual cross-section is bigger than 40 by 60 mm.

The average ignition time of the DRM was higher than the Spruce specimens (Table 2) and the subsequent ANOVA test showed a statistically significant difference at 95% confidence level between the values. White [21] noted that there was a correlation between the times for sustained ignition and the density of various

hardwood species. In this study, higher wood density (DRM) corresponded to higher ignition time while lower density wood species (Spruce) ignited more easily.

3.3 Comparison of temperature profiles for DRM and Spruce

In this section, thermocouples were attached to four specimens along their depth and the specimens were tested in fire without applying any load (see Fig. 4). The objective was to measure the temperature increment along the specimens throughout the time of fire exposure. Comparison between the temperature profiles of DRM and Spruce specimens indicated higher charring rate for the Spruce (Fig. 8). Since timber turns into char at a temperature of 300^{o}C [22,23], it can be seen from the temperature profiles in Fig. 8 measured by thermocouples T1 to T7 that Spruce required less time to reach the charring temperature compared to the DRM specimens. From these figures, it can be concluded that the charring rate was influenced by the different wood species or specifically by the different density of the materials used in this bench-scale fire test.

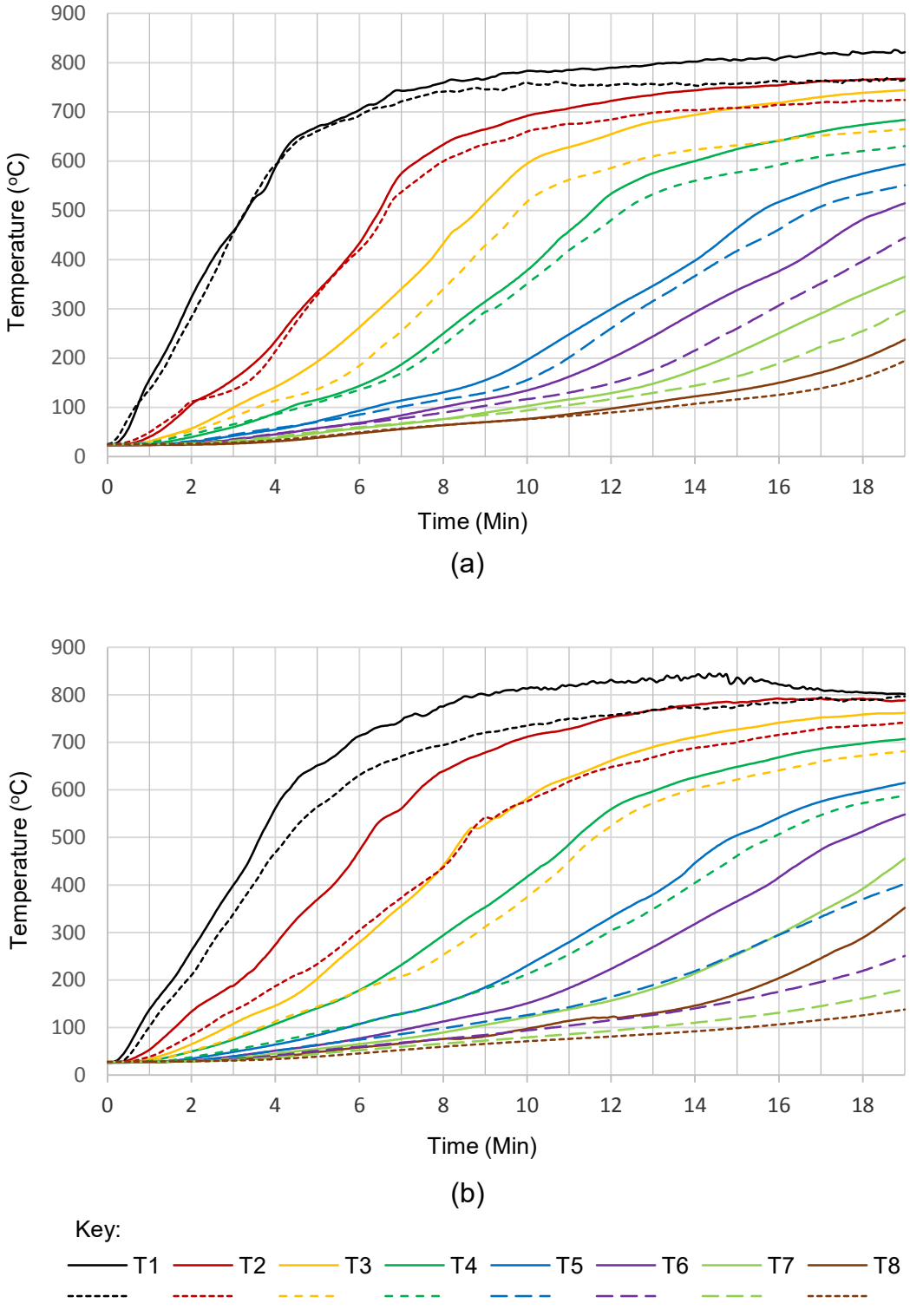

Fig. 8. Temperature profiles of spruce (solid lines) and DRM (dash lines) specimens finger-jointed with (a) PRF; (b) PUR

Fig. 9 shows the char depths of the specimens based on the positions of the thermocouples in relation to the time it takes for the temperature to reach 300^{o}C (timber is completely turned into char at 300^{o}C). It can be seen that the charring rates were not constant. They were higher at the beginning and started to stabilise at a char depth of 20 mm for DRM specimens bonded with PRF and PUR adhesives. The Spruce specimens bonded with PUR stabilised after 25 mm (reduction in char rate) while finger joints with PRF adhesive did not show any trend of stabilizing the char rate.

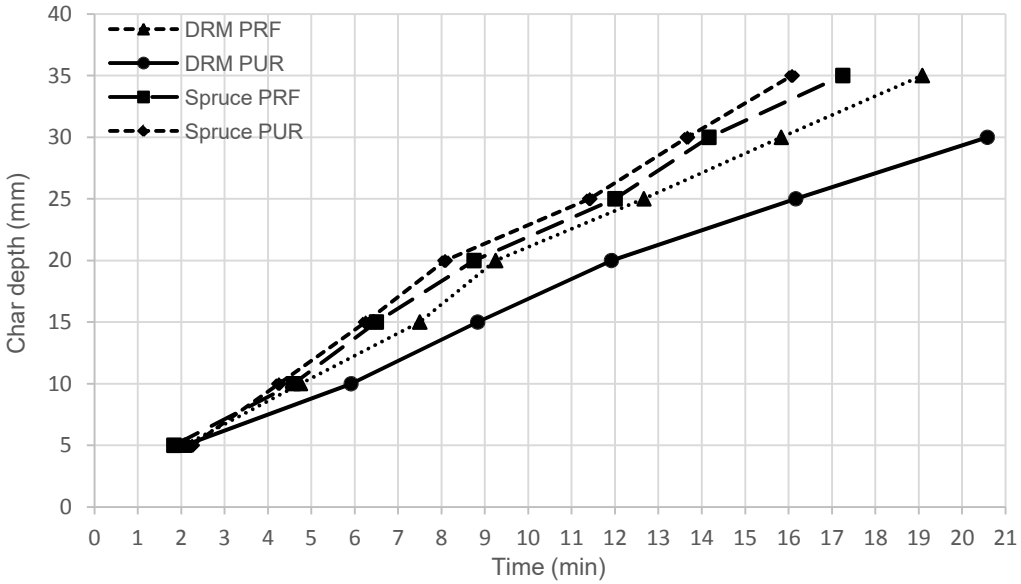

Fig. 9. Char depth as a function of time at a temperature of 300^{o}C

3.4 Influence of density in the tensile strength of finger joints tested at ambient temperature

The average tensile strength of finger-jointed Spruce specimens bonded with PRF (43.1 MPa) and PUR (41.1 MPa) were lower than DRM specimens of PRF (72.8 MPa) and PUR (72.9 MPa) respectively. Typical specimen failures are shown in Fig.

10. The distribution of the tensile strength of the finger-jointed specimens as a function of density when tested at ambient temperature is shown in Fig. 11. A positive relationship can be seen where the tensile strength values increased with increasing density. Comparison between the tensile strength of finger-jointed Spruce and DRM revealed a statistically significant difference at 95% confidence level when tested with ANOVA.

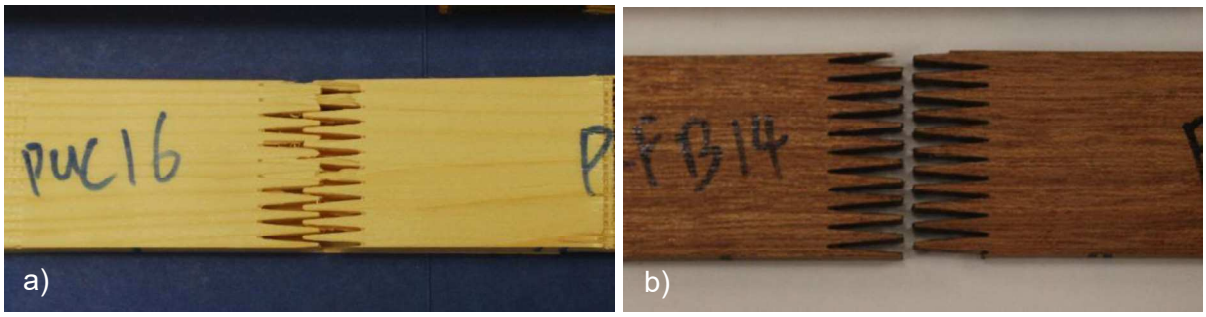

Fig. 10. Typical failures of specimens a) Spruce and b) DRM at ambient temperature

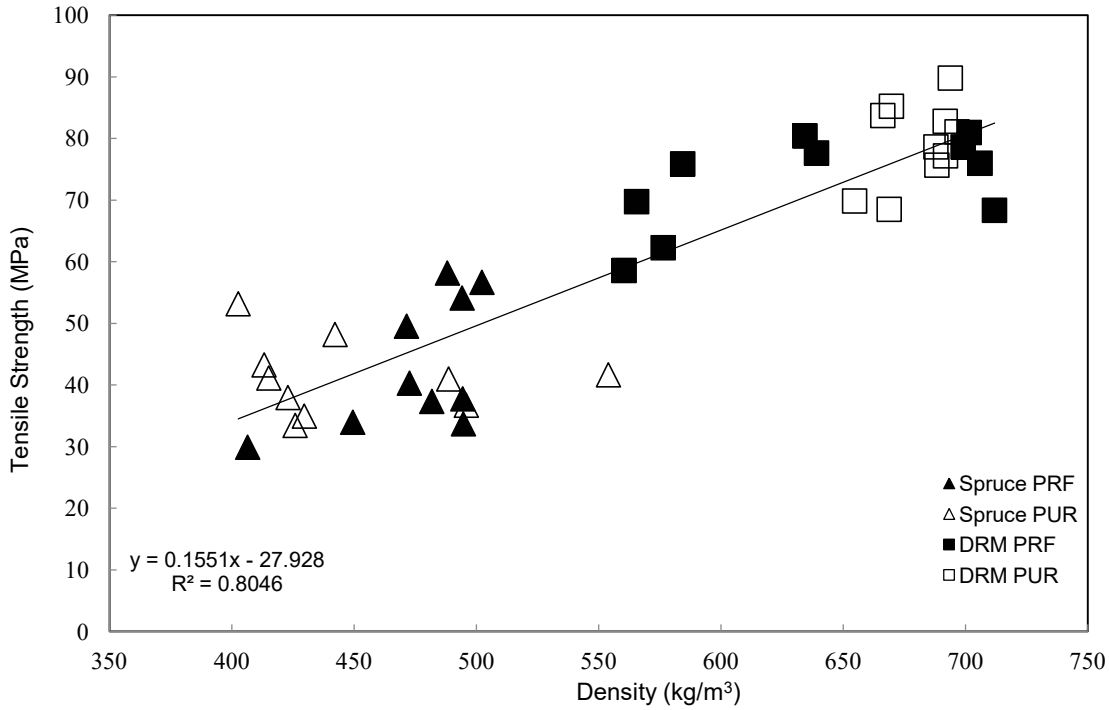

Fig. 11. Tensile strength as a function of density for finger joints tested at ambient temperature

Comparison made between the tensile strength of the finger joints bonded with PRF and PUR for the same species showed no significant difference at a 95% confidence level when analysed with ANOVA for either Spruce or DRM respectively. In contrast, the specimens finger-jointed with PRF showed better performance than PUR when tested using the bench-scale fire tests in this study, indicating the influence of temperature on the tensile strength of the finger joints. The proposed bench-scale fire test set-up is suitable for differentiating the performance of the two investigated adhesives in finger joints in a fire condition.

4. Conclusions

The objective of this bench-scale fire test for finger joints was to provide an easier and less costly set-up with shorter time completion, as an alternative to standard fire resistance tests. The sudden exposure of constant heat-flux was used on the finger-jointed specimens to imitate the conditions of secondary failure in the standard fire test. From these results, comparison can be made between the fire performance of PRF and PUR adhesives by comparing the time to failure and residual cross-section of the specimens. The specimens finger-jointed with PRF showed better fire performance than the PUR adhesive in this study.

The measurement of charring rate is essential in the calculation of the fire safety when designing timber structures. Accurate charring rate results can be used to more accurately calculate the depth of residual cross-sections, optimising the fire design of timber structures. In this study, the charring rate of Spruce was higher than the DRM specimens because of the higher density of the latter species. Overall, the charring rate results in this study were much higher than the published values in

other papers. The possible reasons were the influence of factors such as the constant heat flux in contrast to time-increasing heat-flux and the smaller size of the specimens. Importantly, the charring rate in this study was measured in the early period of the fire test, where the char rate is higher because of the lack of insulating charred layer protecting the inner unburnt wood.

In the tensile test at ambient temperature, the DRM specimens possessed higher strength than Spruce specimens. Comparison between finger joints bonded with PRF and PUR did not show any significant difference in tensile strength, contrary to the bench-scale fire test where PRF finger joints showed better residual tensile strength than PUR. It can be concluded that temperature plays a role in influencing the tensile strength of the finger joints bonded with different adhesives. The bench-scale fire test is able to quickly differentiate and evaluate the quality of different adhesives for finger joints for structural use in fire conditions. Further tests are needed to verify the results of this bench-scale fire test in comparison to the standard full-size fire test and to find a correlation especially for conditions where secondary failure of the glulam beam occurs. At present, constant charring rate with time is commonly used in fire design with the assumption that non-linearity does not significantly influence the resistance of timber structures when exposed to fire.

Acknowledgements

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