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FIRE PERFORMANCE OF HARDWOOD FINGER JOINTS

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ABSTRACT: This paper investigates the performance of Malaysian hardwood, dark red meranti finger joints in fire. Finger joints were prepared using two load-bearing type adhesives and tested in tension by means of a bench-scale fire test. They were tested in tension to replicate the failure of finger joints in tension layers of a glulam beam, which commonly occurs in a standard fire resistance test. Finger joints from softwood were also prepared and tested for comparison purposes. In addition, tensile tests at ambient temperature were conducted for both the hardwood and softwood finger joints in order to determine the approximate load level applied during the bench-scale fire tests. The time to failure, residual cross section and charring rate were determined and analysed. Results showed that the type of adhesive significantly influenced the time to failure. Furthermore, a lower residual cross-section was found in the finger joints bonded with phenol resorcinol formaldehyde (PRF) compared to the finger-jointed polyurethane (PUR) specimens. Therefore, PRF is better able to resist fire tests, has a higher residual strength and a longer time to failure compared to PUR.

KEYWORDS: finger joints, hardwood, fire performance, adhesive

1 INTRODUCTION

One of the important factors that determines the fire resistance of a glulam beam is the performance of finger joints located in the middle region of the outermost tension layers. In a standard fire test for glulam, the beam is tested in four-point bending with the compressive side on the top being fire-protected. Failure normally occurs on the lowest tension side of the beam. Thus, a tensile test was preferred in this study since the tension face of a beam experiences the highest stress [1]. The tension face is normally exposed to fire, thus weak fire performance of finger joints on the tension layers may influence the time to failure of the beam. Lack of research conducted in particular on finger-jointed hardwood species also hinders efforts to predict accurately the time to failure of finger joints in a glulam beam under fire condition. Previous studies suggested using tensile tests to test finger joints at elevated temperature and concluded that they were suitable for determining the fire performance of the finger-jointed specimens, where a substantial reduction in strength was seen with increasing temperature [2,3].

In this study, a bench-scale fire test method developed at SP Wood Building Technology, Sweden was used. This small-scale finger joints under fire condition setup was preferred compared to the large-scale fire tests which were more expensive and may not always provide additional information for better understanding of the performance of finger joints in fire.

There were attempts to develop bench-scale fire test method for finger joints. Klippel *et al*. [4] investigated the performance of small-scale finger joints in tension at elevated temperature while using adhesives commonly used in the large-scale fire tests. They were aiming to further develop the small-scale testing method and compare the test results with the large-scale fire tests, leading to the possibility of standardizing the small-scale test method to be used in Europe. Craft *et al*. [5] developed a small-scale tension test method to evaluate the performance of finger joints bonded with different adhesives at elevated temperature. The test method was designed based on the modification of existing standard testing methods from ASTM and the Canadian Standards Association.

In this paper, comparison was made between two different adhesives and their effects on the time to failure in the bench-scale cone fire tests. In addition, the charring rate and residual cross-section of the hardwood and softwood species were evaluated. Tensile tests at ambient temperature were also conducted for reference purposes.

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2 MATERIALS AND METHOD

2.1 MATERIALS

The wood species used for the finger-jointed specimens were Malaysian dark red meranti (DRM) and Norway spruce. Phenol resorcinol formaldehyde and polyurethane adhesives were used as the bonding media for the finger joints. The density of the DRM was in the range of 560 to 712 kg/m^3 with an average moisture content of 13%. The density of the spruce was between 403 to 554 kg/m^3 with an average moisture content of 11%. The wood species were preconditioned in a conditioning room at a temperature of 20ºC and relative humidity of 65%. Ten finger-jointed specimens were produced from each of the wood species and each type of adhesives, totalling 40 specimens for the cone tests and another 40 specimens for the tensile tests in ambient temperature.

2.2 SPECIMEN PREPARATION

The finger profiles were cut from wide timber pieces of the size (thickness x width x length) of 51 x 99 x 620 mm (DRM) and 44 x 115 x 620 mm (spruce) using the manual feed finger cutter machine at SP Wood Building Technology (Figure 1). They were then bonded on the same day using adequate pressure with glue squeeze-out observed during cramping. The finger-jointed pieces were then left to cure for two weeks to allow the joints to reach optimum strength, as recommended by the adhesives supplier. The finger-jointed pieces were then cut and ripped to the specimen size of 10 x 42 x 300 mm (Figure 2).

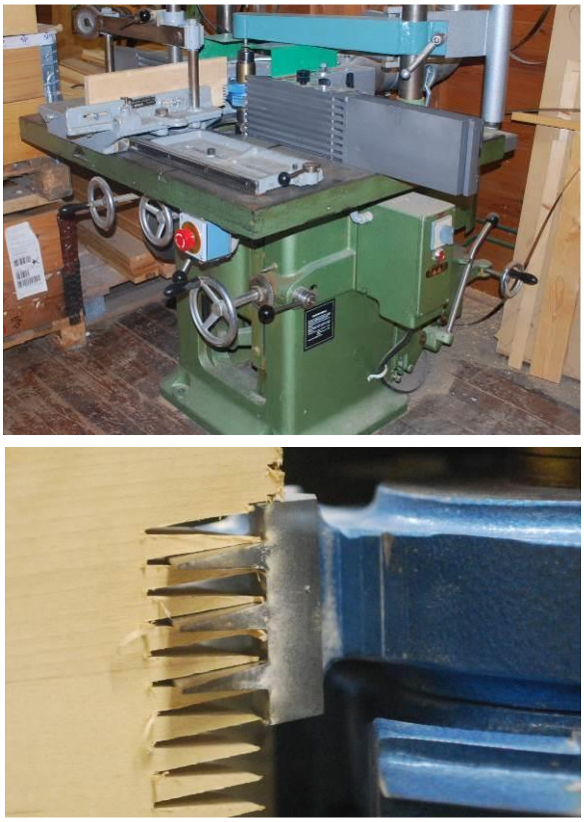


Figure 1: *Finger joint machine (top) and cutter (bottom)*

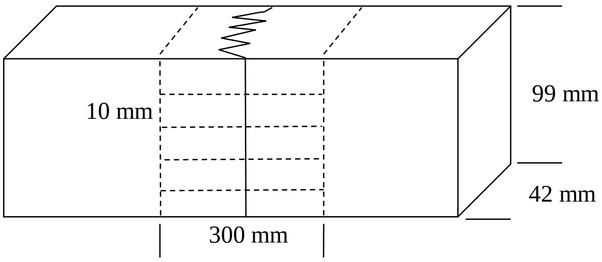


Figure 2: *DRM specimens cutting arrangement*

The number of specimens for each test with different adhesives is shown in Table 1.

Table 1: *Test specimens*

Specimen	Test Condition	Adhesive	Quantity
DRM	Fire	PRF	10
DRM	Fire	PUR	10
DRM	Ambient	PRF	10
DRM	Ambient	PUR	10
spruce	Fire	PRF	10
spruce	Fire	PUR	10
spruce	Ambient	PRF	10
spruce	Ambient	PUR	10
DRM	Thermocouple	PRF	1
DRM	Thermocouple	PUR	1
spruce	Thermocouple	PRF	1
spruce	Thermocouple	PUR	1

Additional specimens were also made from each of the wood species and adhesives to accommodate attachment of thermocouples. Eight thermocouples were used for measuring internal temperatures at the finger joints region when tested in the fire condition. The thermocouples were attached at different depths and staggered locations (Figure 3). The positions of the thermocouples are specified in Section 3.1. Small holes with diameter of 0.5 mm were drilled into the mid-section of the wood, allowing the tip of the thermocouples to be inserted into the internal of the specimen for accurate measurements.

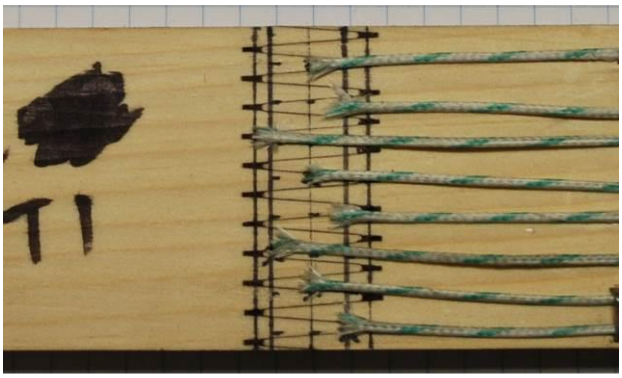


Figure 3: *Thermocouples attached to the finger joints region*

2.3 FINGER JOINT CONFIGURATION

Figure 4 shows the bonded finger joints of DRM and spruce specimens. The length of the finger joints was 15 mm and the specimens contained vertical joints, which are commonly used for structural uses. The pitch of the finger joints was 3.8 mm, with the tip width and tip gap approximately 0.6 mm and 1.4 mm respectively. Careful observation was made to select specimens which had no significant defects and knots near the finger joints and testing region. This was important to avoid failures from occurring because of these factors and only the resulting performance of the finger joints was analysed.

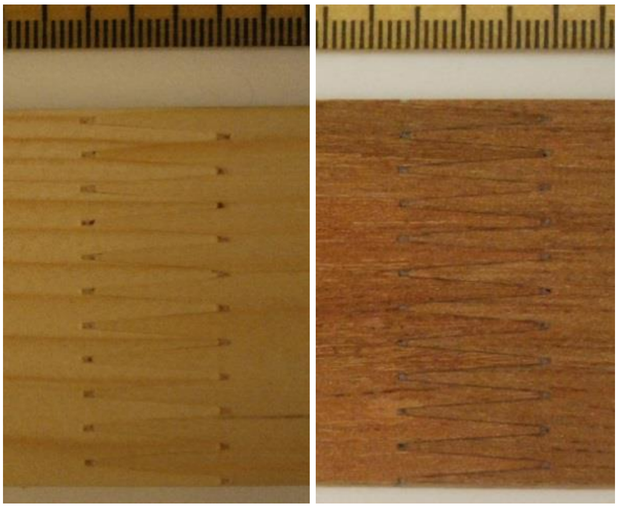


Figure 4: *Finger joints of spruce (left) and DRM (right)*

2.4 EXPERIMENTAL SETUP

2.4.1 Cone test

The bench-scale fire tests were conducted using a cone heater and a pre-determined constant load of 2.5 kN. The load was approximately 10% of the ultimate load of the reference finger joints from the tensile tests in ambient temperature. Prior to the fire tests, reinforcements using plywood were bonded to the gripping sections of the specimens to prevent failure at the end of the pieces and encouraging failure at the heated finger joints area. Holes were drilled at the reinforced area of the specimens for anchoring purposes (Figure 5).

Figure 5: *Reinforcement at the end sections*

In the fire tests, the specimen was arranged with stone wool protecting both sides, limiting the exposure of heat to one edge only (Figure 6). Fibre glass wool was used to protect the top of the specimen before the start of the fire tests (Figure 7). Prior to the test, the distance between the cone heater and the top surface of the specimen was also measured. Then, a gauge was fixed at the same position as the top surface of the specimen to measure the temperature when exposed to the heat flux. The temperature of 657°C was measured with a constant heat flux of 50 kW/m^2.

Figure 6: *Stone wool protecting the sides of the specimen*

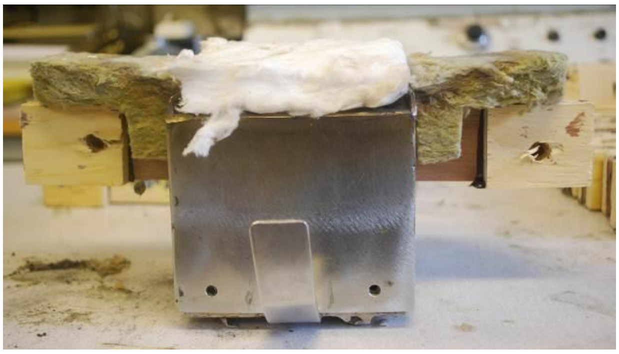


Figure 7: *Fibre glass wool on top of the specimen prior to the fire test*

Once the specimen was placed under the cone heater, the fibre glass wool protecting the top surface of the specimen was removed. The constant heat flux of 50 kW/m^2 was introduced to the specimens with dead weights applied at the same time (Figure 8). Ignition was observed inside the first minute of the tests. The duration of the tests was up to 16 minutes, depending on the type of wood species and adhesive being tested. Once the finger joints failed, the specimen was quickly removed from the heating area and soaked in water to extinguish the fire. This is important to ensure only the residual cross-section during the fire test was measured. The time to failure and charring rate were determined after the tests. The charring rate was calculated based on the ratio of charring depth to time.

Figure 8: *Bench-scale fire test with dead weights (top) and ignition (bottom)*

Specimens with thermocouples attached to the finger joints area were also tested in the same way as the typical joints but without loading the dead weights (Figure 9). The thermocouples were attached to a data logger and the increasing temperature during the tests was recorded in a computer. The purpose was to observe the profile of temperature along the whole depth of the specimens during the fire tests.

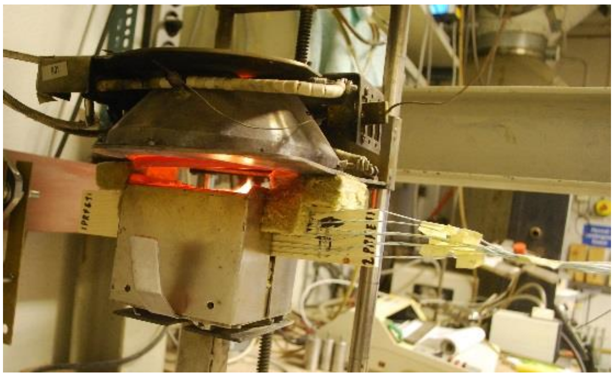


Figure 9: *Specimen attached with thermocouples*

2.4.2 Tensile test at ambient temperature

Tensile tests at ambient temperature were conducted for the finger-jointed specimens. A universal testing machine with a maximum load of 50 kN and a cross-head speed adjusted to 5 mm/min was used. The specimen was gripped approximately 80 mm in length at both ends with the finger joints positioned in the middle (Figure 10). The specimen was properly aligned so that the application of load did not induce bending. The maximum load was recorded and the tensile strength was calculated. After each test, the remaining undamaged sections of the test pieces were cut for determination of moisture content and density.

Figure 10: *Tensile test in ambient temperature setup*

3 RESULTS AND DISCUSSION

3.1 TENSILE TEST IN FIRE CONDITION

Typical failures of the finger-jointed specimens after testing in fire are shown in Figures 11 (DRM) and 12 (spruce). Almost all failures occurred at the glue lines of the finger joints with mixture of wood fibre tear-out and adhesive failures. Adhesive failures occurred mostly near the charred region because of the higher temperature that may have softened the glue lines. Few specimens failed in the wood where splitting occurred near knots or along the slope of grain (Figure 13).

Figure 11: *Typical failures of DRM finger joints bonded with PUR (top) and PRF (bottom) after fire tests*

Figure 12: *Typical failures of spruce finger joints bonded with PUR (top) and PRF (bottom) after fire tests*

Figure 13: *Failures near knots (top) and along the slope of grain (bottom)*

The average time to failure (TTF), residual cross-section (A_r) and charring rate (β) are shown in Table 2. The average charring rate for DRM and spruce in the fire tests was much higher when compared to the one-dimensional design charring rate, β_0 and notional charring rate, β_n (includes the effect of corner roundings and fissures) published in BS EN 1995-1-2 [6]. The published design values were β_0 = 0.65 mm/min and β_n = 0.8 mm/min for solid softwood and beech timber; β_0 = 0.50 mm/min and β_n = 0.55 mm/min for solid hardwood timber respectively. The higher charring rate of the specimens in this study may be caused by the inadequate insulation at the sides of the specimens. In addition, the specimens were much smaller compared to the larger timber members like glulam which have larger outer sections of charcoal protecting the inner sections from increasing in temperature when tested in standard full size fire tests.

Table 2: *Finger joints cone test results (average)*

Species (adhesive)	TTF (min)	A_r (mm^2)	β (mm/min)
$Spruce_{(PRF)}$	7.60 (1.12)*	264.32	1.97 (0.27)
$Spruce_{(PUR)}$	5.47 (0.93)	310.73	1.97 (0.26)
$DRM_{(PRF)}$	11.27 (2.38)	243.97	1.58 (0.37)
$DRM_{(PUR)}$	6.53 (1.28)	322.91	1.47 (0.14)

*Standard deviation in parentheses

The charring rate of DRM was lower than spruce for both finger-jointed specimens bonded with different adhesives as expected (Figures 14 and 15). A one way analysis of variance (ANOVA) test was used and the results indicate statistically significant difference at 95% confidence level between the charring rate values of DRM and spruce. The results agree with the literature such that increasing density will decrease the charring rate in a fire test [7-9]. However, further tests were needed to determine whether the charring rate could be solely influenced by either the density or moisture content in this bench-scale fire tests.

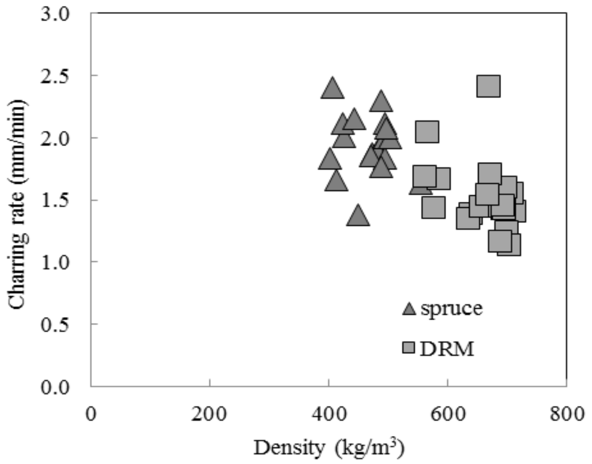


Figure 14: *Charring rate versus density of finger-jointed DRM and spruce specimens*

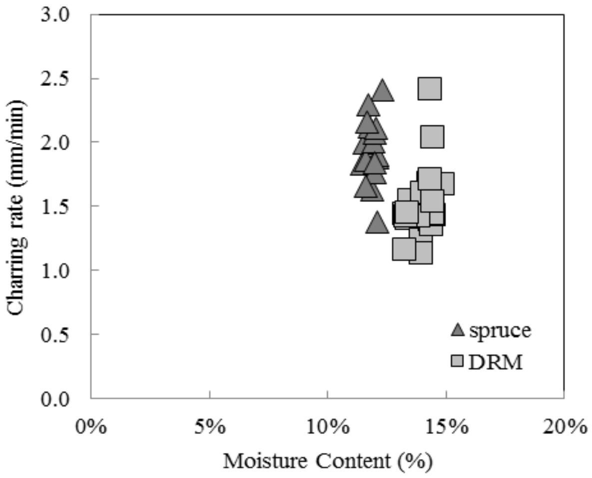


Figure 15: *Charring rate versus MC of finger-jointed DRM and spruce specimens*

The average time to failure for both the DRM and spruce specimens bonded with PRF were higher than the specimens finger-jointed with PUR adhesive. The results from ANOVA analysis indicate significant difference at 95% confidence level in the time to failure values. The residual cross-section of the PRF finger joints for both species also showed lower values than the specimens finger-jointed with PUR adhesive. The results indicated that the specimens finger-jointed with PRF showed better fire performance than the PUR finger joints. The PUR adhesive was more likely to fail viscoelastically at elevated temperature as it was less likely to be full cross-linked whereas the PRF was less likely to yield. The results also agreed well with the findings of Frangi *et al*. [2] where different strength reductions of finger-joints tested in tension at elevated temperature were observed when using different types of structural adhesives. Nevertheless, Klippel *et al*. [4] stated that there were variations in the one-component polyurethane adhesive systems and the test results of one PUR may not be representative of other PUR adhesive systems.

The average charring rate for the same timber species showed no difference when bonded with PRF or PUR (Table 2). This may indicates that the bonding in the finger joints did not influence the charring rate. The possible reason is that the bonding area was small compared to the cross-sectional area of the finger-jointed specimen, thus not contributing significantly to the fire resistance.

The temperatures across the finger-jointed specimens were recorded using eight thermocouples. The first thermocouple (T1) was positioned at the distance of 5 mm from the top exposed surface and the subsequent thermocouples (T2 to T8) were located every 5 mm across the width of the specimens (Figure 3).

The increasing temperature of the corresponding thermocouples at different locations in the finger jointed specimens are shown in Figures 16 (spruce) and 17 (DRM), in relation to the time period of the tests. The temperature profiles look similar for the same timber species regardless of the adhesives used. In comparison between the wood species, DRM showed a slower rate of increase in temperature than spruce.

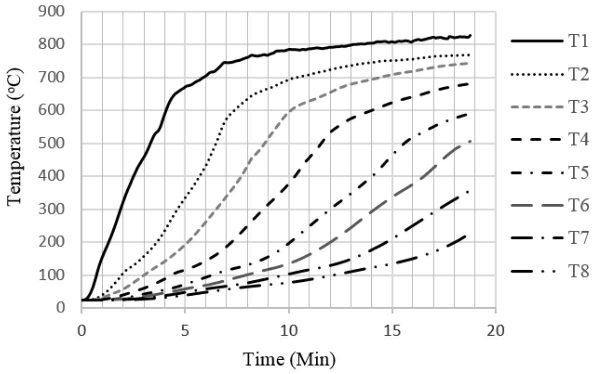
The average time to failure (Table 2) occurred after 5.47 and 6.53 minutes for specimens of spruce and DRM respectively bonded with PUR. Based on this short time to failure, Figures 16 (b) and 17 (b) show that only thermocouples T1 and T2, reached 300°C (charring starts to develop at this temperature [10]). Since the finger-jointed specimens were small, the char depth was only approximately 10 mm (location of T2) when the specimens bonded with PUR started to fail.

The specimens bonded with PRF showed average time to failure of 7.60 and 11.27 minutes for spruce and DRM respectively. In Figures 16 (a) and 17 (a), thermocouples T1 to T3 and thermocouples T1 to T4 respectively, exceeded the temperature of 300°C. Thus, the char depths were approximately 15 mm (location of T3) and 20 mm (location of T4) when the specimens bonded with PRF started to fail.

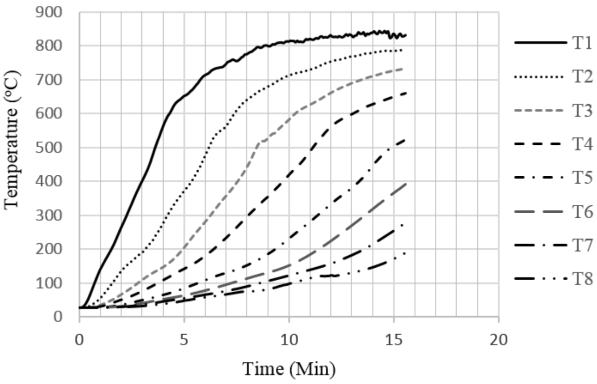
The approximation of char depth values from Figures 16 and 17 augurs well with the char depth calculated from simple subtraction of the specimen's initial depth before test and the average measured residual depth of the tested finger-jointed specimens (Table 3).

Table 3: *Average of measured residual depth and calculated char depth*

Species (adhesive)	Measured residual depth (mm)	Calculated char depth (mm)
$Spruce_{(PRF)}$	26.40	14.87
$Spruce_{(PUR)}$	31.12	10.70
$DRM_{(PRF)}$	24.77	17.05
$DRM_{(PUR)}$	32.58	9.51

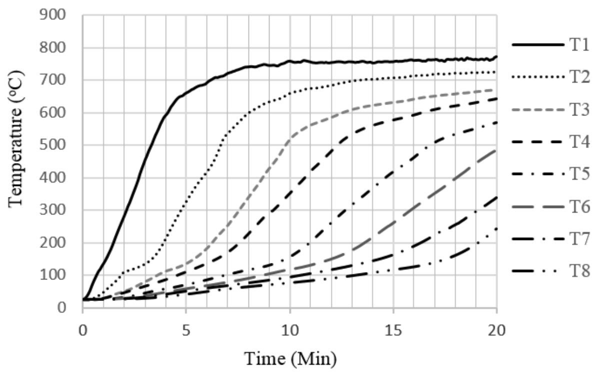


(a)

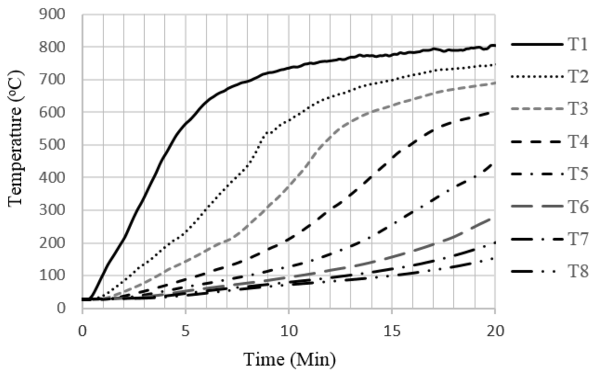


(b)

Figure 16: *Temperature across finger-jointed spruce specimens bonded with (a) PRF; (b) PUR*



(a)



(b)

Figure 17: *Temperature across finger-jointed DRM specimens bonded with (a) PRF; (b) PUR*

3.2 TENSILE TEST AT AMBIENT TEMPERATURE

The average tensile strength of DRM finger-jointed with PRF and PUR were higher than the spruce when tested at ambient temperature (Table 4). Figure 18 showed the tensile strength of both spruce and DRM with their corresponding density. DRM with higher density exhibits higher tensile strength compared to spruce.

In Table 4, the average tensile strength of finger joints bonded with different adhesives was similar for the same timber species. In contrast, the PRF finger joints performed better compared to PUR in the fire tests. Therefore, temperature influences the tensile strength of finger-jointed specimens bonded with different adhesives in this study.

Table 4: *Tensile strength of finger joints*

Species (adhesive)	Tensile strength (MPa)	
	Mean	Standard deviation
$Spruce_{(PRF)}$	43.13	10.49
$Spruce_{(PUR)}$	41.13	6.03
$DRM_{(PRF)}$	72.84	7.77
$DRM_{(PUR)}$	72.94	6.71

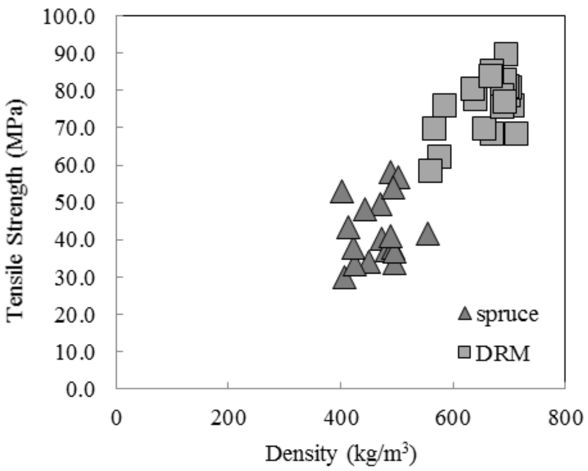


Figure 18: *Tensile strength versus density for DRM and spruce finger-jointed specimens*

Observation of the mode of failure for DRM specimens finger-jointed with PRF showed failures mainly at the glue lines of the finger joints while with PUR, the majority of the failures occurred both at the glue lines and by splitting of wood (Figure 19). Further inspection of the failed glue lines showed a mixture of a large amount of wood fibre pull-out and adhesive failures (Figure 20). Higher rate of wood fibre pull-out typically indicates good bonding performance.

Figure 19: *Failure of finger joints and wood for DRM specimens bonded with PRF (top) and PUR (bottom)*

Figure 20: *Mixture of wood fibre pull-out and adhesive failures in the glue lines*

4 CONCLUSIONS

The results of this study showed that the types of adhesive influenced the time to failure of finger joints tested in tension in the bench-scale fire tests. Finger joints bonded with PRF adhesive showed better performance in fire condition with higher time to failure and lower residual cross-section compared to PUR. In contrast, the type of adhesive had no effect on charring rate.

The higher density DRM species with lower moisture content charred more slowly compared to spruce. It can be concluded that density and moisture content may play a role in influencing the charring rate of the finger-jointed timber. Nevertheless, further investigation is needed to determine the individual contributing factors that may influence the charring rate by using specimens of the same density range but different moisture content and vice versa.

At ambient temperature, the tensile strength of DRM specimens was higher than the spruce. There were no differences in tensile strength when comparing the finger joints bonded with PRF and PUR adhesives.

This simple bench-scale fire test arrangement provides a clear indication of the performance of different adhesives in the finger joints subjected to fire conditions without the need to perform the full size standard fire tests. Future work should include testing of finger joints in large-scale fire tests using the same types of specimens and adhesives, and comparing the results obtained to the bench-scale fire tests. Further development of the bench-scale fire test can be made and standardized so it may be possible to accurately determine the performance of adhesives in fire conditions for structural products.

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REFERENCES

[1] Ong C. B.: Glue-laminated timber (Glulam). In Ansell M. P., editor, *Wood Composites*, pages 123-140. Woodhead Publishing, 2015.

[2] Frangi A., Bertocchi M., Clauß S., Niemz P.: Mechanical behaviour of finger joints at elevated temperatures. Wood Science and Technology, 46:793-812, 2012.

[3] Klippel M., Frangi A., Fontana M.: Influence of the adhesive on the load-carrying capacity of glued laminated timber members in fire. Fire Safety Science, 10:1219-1232, 2011.

[4] Klippel M., Clauß S., Frangi A.: Experimental analysis on small-scale finger-jointed specimens at elevated temperatures. European Journal of Wood and Wood Products, 72(4):535-545, 2014.

[5] Craft S. T., Desjardins R., Richardson L. R.: Development of small-scale evaluation methods for wood adhesives at elevated temperatures. In: *10th World Conference on Timber Engineering*, pages 583-590, 2008.

[6] BS EN 1995-1-2: Eurocode 5, Design of timber structures, Part 1-2: General – Structural fire design. British Standards Institution, 2004.

[7] Yang T. H., Wang S. Y., Tsai M. J., Lin C. Y.: The charring depth and charring rate of glued laminated timber after a standard fire exposure test. Building and Environment, 44(2):231-236, 2009.

[8] Njankouo J. M., Dotreppe J. C., Franssen J. M.: Experimental study of the charring rate of tropical hardwoods. Fire and Materials, 28(1):15-24, 2004.

[9] Cachim P. B., Franssen J. M.: Assessment of Eurocode 5 charring rate calculation methods. Fire Technology, 46(1):169-181, 2010.

[10] Brandon D., Ansell M. P., Harris R., Walker P., Bregulla J.: Modelling of non-metallic timber connections at elevated temperatures. In Aicher S., Reinhardt H.-W., Garrecht H., editors, *Materials and Joints in Timber Structures*, pages 231-241. Springer Netherlands, 2014.