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EFFECT OF ADHESIVE AND SPECIES ON INTERFACE PROPERTIES OF TIMBER LAMINATES

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ABSTRACT: In recent years, wood veneers is gaining attention for its use in automotive application, since they require significantly less energy to produce while act as carbon sink. However, studies on the interface properties of wood veneers are limited in literature. This paper evaluates interface properties between thin veneer sheets by means of mode I fracture testing. At first, European beech, laminated using 1-part polyurethane, was compared against bio-epoxy laminated beech veneers. Bio-epoxy was selected to increase the sustainability aspect of the laminated timber products which contained 77% plant-based ingredients. Use of epoxy is beneficial, since it has long gel time that allows more time to form complex shapes. Another advantage of using epoxy is the possibility of heat curing at higher temperature due to its higher glass transition temperature compared to its polyurethane counterpart. This, in turn, support fast manufacturing which is important for the automotive industry. Therefore, the effect of heat curing duration and temperature for epoxy bonded beech veneers are also examined in this study. Moreover, to diversify the use of various species in laminated timber products, interface properties between other species were also investigated. Two hardwood (European beech and Tasmanian oak) and one softwood (hoop pine) species were considered in this regard.

KEYWORDS: fracture, interface, adhesive, hardwood, softwood

1 – INTRODUCTION

Wood is well known for its low energy requirements to produce various products, such as, veneers or sawn boards. In addition, the biogenic aspect of wood makes it a carbon negative material [1]. With the advancement of mass engineered wood products, e.g., laminated veneer lumber and glue / cross laminated timber, use of wood for structural engineering application has reached new dimensions in recent years. Mass engineered wood products are now used for mid to high rise buildings and bridges. However, the use of wood in automotive and aviation industry was found to be diminished after World War II [2].

In recent years, wood is again found to be considered as suitable and desirable alternative in aviation and automotive industry. Three French companies are now offering light aircraft made of wood that includes Aura aero [3], Mauboussin Aircrafts [4] and Robin Aircraft [5]. For automotive parts, it often requires complex shapes which can be formed relatively easily using thin veneers compared to solid sawn wood. Use of veneers also ensure efficient use of natural resources, compared to conventional sawn woods. Also, mixing of species is possible that reduces the demand on single species, promoting biodiversity [6]. Lastly, thin veneers can be sourced from small logs compared to sawn boards acquired from larger logs. Thus, use of veneers enables faster recovery rates of natural forests [7].

Literature on the use of veneers for structural applications is limited. The species which are used for this purpose are also restricted to a handful ones, which includes European beech [8], poplar [9], oak and birch [10] in relation to automotive applications. For structural engineering applications, circular hollow sections using Eucalyptus cloeziana veneers [7, 11] and channel section using hoop pine veneers [12, 13] were reported in literature. Commonly used adhesives used in these studies includes polyurethane (PUR) and resorcinol formaldehyde, since their efficiency in bonding wood veneers are well known. However, both these adhesives, especially resorcinol formaldehyde is highly toxic which affects the sustainability aspect of timber. In this study, a sustainable alternative is proposed using bio-epoxy which was found to be effective in bonding of fibre reinforced polymer composites [14].

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Use of epoxy for bonding veneers can be beneficial for numerous purposes. For complex shapes of the structural elements used in automotive applications, epoxy can be better suited to form different shape compared to its PUR counterpart. This is due to epoxy's lower viscosity compared to the same of PUR's. Based on the viscosity properties of epoxy and PUR, PUR can be 10 times more viscous than the former (refer to Section 2.2 for details). This is beneficial for forming complex shapes, especially at the bending region of the veneers. Moreover, fast manufacturing is expected in automotive industry and heat curing can be beneficial to expedite the curing process. However, use of heat curing for PUR is limited since its glass transition temperature is 50°C, whereas epoxy can be heat cured up to 120 – 150 °C. In this paper, an effort was made to optimise the curing temperature and duration for wood laminates to reduce the curing time for the epoxy bonded wood laminates.

While veneers were used in some of the aforementioned studies, it is not well known how the interface characteristics get affected due to the difference in species, adhesive, and curing conditions are still not well known. Mode I fracture properties of some species were estimated in a few studies [15-17] to characterise the interface properties of timber-PUR or timber-epoxy interface. However, these results are associated with thick sawn wood. It is reported that thickness of the veneers have an impact on the mechanical performance of the final product [18]. Hence, interface properties of thin veneers require further investigation.

This paper compares the mode I fracture properties of three species – two hardwood and one softwood. European beech (hardwood) laminated bonded using PUR is considered as the benchmark due to the extensive works undertaken by the authors previously [8, 19]. This benchmark value is then compared against two Australian species – Tasmanian oak and hoop pine which are hardwood and softwood, respectively. Furthermore, the interface characteristics of the epoxy bonded beech laminates, cured under various conditions, are examined to determine its efficacy in bonding timber laminates.

2 – PROJECT DESCRIPTION

2.1 EXPERIMENTAL PROGRAM

Mode I testing was undertaken in this study to evaluate the interface characteristics of various wood veneers in combination with two type of adhesive system – one component polyurethane (PUR) and bio-epoxy (Epx). The effect of species and adhesive system were investigated in three phases as follows:

Phase 1: comparing Australian hardwood species (Tasmanian oak) against the benchmark value

In this phase, mode I interlaminar fracture property (G_I) of Tasmanian oak is compared against European beech. In this phase, only PUR is considered for comparison.

Phase 2: comparing epoxy against PUR as adhesive

Bio-epoxy is chosen as an alternative adhesive system. At first, ambient cured epoxy is compared against the benchmark PUR based European beech veneers laminates. The comparison is made in terms of load vs displacement curve and G_I. Following the ambient curing, curing duration and temperature were varied to assess the performance of the bio-epoxy bonded beech veneer laminates. The Col. (3) of Table 1 summarises the curing condition and duration.

Phase 3: comparing Australian softwood (hoop pine) against beech

For hoop pine, only epoxy with different curing durations was considered. The curing temperature was selected from Phase 2, and the mode I interlaminar fracture property of hoop pine was then compared against European beech subjected to the same curing conditions. The Col. (1 – 3) of Table 1 outlines all the variables considered in this study including all the three phases discussed in this section.

2.2 MATERIALS

Rotary cut European beech with an average density of 720 kg/m^3 was used in this study. The veneers were provided by Metz & Co, Germany with an average thickness of 0.6 mm. The Hoop pine and Tasmanian oak were provided by Briggs Veneer with initial thickness of 0.6 mm as well. However, the Hoop pine was crown cut, whereas the Tasmanian oak was quarter cut. The average density of the hoop pine and Tasmanian oak were 530 and 650 kg/m^3, respectively.

Fast curing polyurethane was selected in this study, since fast manufacturing is one of the main objectives of this study. One component PUR (PURBOND HB S109), supplied by Henkel, was chosen. HB S109 has a density of 1160 kg/m^3 with a viscosity of 24,000 mPa.s. The recommended assembly and pressing time for HB S109 is less than 10 mins and 25 – 75 mins, respectively. The two-part bio-epoxy (CCBE-5) adhesive used in this study was supplied by Change Climate Pty Ltd. The mixing ratio between Part A and Part B was 71.5 to 28.5 by volume. The mixed density was 1150 kg/m^3 with viscosity of 2,300 mPa.s. The glass transition temperature of the bio-epoxy and PUR used in this study were 150 and 50 °C, respectively.

2.3 SAMPLE PREPARATION

The size of the test specimen to determine mode I fracture toughness was selected based on ASTM 5528: Standard Test Method for Mode I Interlaminar Fracture Toughness of Unidirectional Fiber-Reinforced Polymer Matrix Composites [20].

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TABLE 1: EXPERIMENTAL PROGRAM

Col. (1)	Col. (2)	Col. (3)	Col. (4)	Col. (5)	Col. (6)
Species	**Adhesive**	**Conditioning**	**Final thickness (mm)**	**G_I in J/m^2 (± SD)**	**Ratio (G_I) w.r.to Beech**
European beech	Polyurethane	Ambient cured (24 hours)	3.80	598.54 (± 22.05)	1.00
Tasmanian oak	Polyurethane	Ambient cured (24 hours)	3.80	498.89 (± 11.89)	0.83
European beech	Epoxy	Ambient cured (24 hours)	3.70	306.69 (± 35.71)	0.51
European beech	Epoxy	4 hours at 100°C	4.78	176.14 (± 28.65)	0.29
European beech	Epoxy	4 hours at 120°C	4.60	486.23	0.81
European beech	Epoxy	10 hours at 100°C	4.80	258.05 (± 36.78)	0.43
European beech	Epoxy	10 hours at 120°C	4.30	495.92	0.83
Hoop pine	Epoxy	4 hours at 100°C	4.50	-	-
Hoop pine	Epoxy	10 hours at 100°C	4.45	-	-

The authors [8] previously reported that the double cantilever beam (DCB) method outlined in ASTM5528 is suitable to determine mode I fracture properties for wood veneer laminates. Figure 1(a) shows the schematic of the DCB test sample. A total of 8 uni-directional plies were used to make specimens outlined in Table 1 to obtain a thickness between 3 – 5 mm, as per the standard. The sample preparation steps can be broadly divided into four stages as follows:

Veneer preparation

At first, the veneers were flattened, since some of the veneers came into roll. Conditioning was done at 23°C and 65% relative humidity to obtain 12% moisture content. Some dead weight was applied on the veneers to ensure flattening. Then the veneers were cut into 8 equal pieces (each representing one layer) to match the desired panel size. The panel size was chosen to obtain multiple samples, as per Figure 1, of the same group. Some physical properties, such as, density and moisture were measured.

Gluing

Part A and B of the bio-epoxy were mixed before its application on the veneer surfaces. One-component PUR was used in this study that eliminates any premixing. Then, the glue was spread on the top side of the 7 (out of 8 layers) cut veneers at a rate of 160 g/m^2 for PUR and 180 g/m^2 for bio-epoxy. A plastic spreader was used to distribute the adhesive uniformly on each surface of a veneer before bonding with the adjacent one. Time taken for the glueing and assembling was varied between 4 – 7 minutes which was under the recommended assembly time of 10 minutes for PUR. The moisture of the veneers varied between 9 – 12 % which was within the limit of 8 – 18% for PUR bonding.

Pressing and conditioning

After the stacking of 8 layers, the panels were subjected to a pressure of 1 MPa, irrespective of the adhesive or species used. The PUR and ambient-cured beech-epoxy samples in Table 1 were pressed for 24 hours at ambient temperature. The hot-pressed samples at 100 and 120°C were pressed for 4 and 10 hours before testing, as mentioned in Col. (3) of Table 1. Once the pressing was completed, the final thickness was measured and listed in Col. (4) of Table 1. It is evident from the final thickness values that longer pressing duration caused more densification of timber, resulting in lower thickness, compared to shorter pressing duration. Densification is unavoidable during pressing process. However, for shorter pressing duration, densification was relatively negligible, whereas approximately 1 mm of densification was observed for 24hours pressed samples.

Samples cutting

Following the pressing / conditioning, each panel was cut into multiples samples containing the dimensions depicted in Figure 1(a). At least 3 samples were prepared for each group tabulated in Table 1. The pre-notch length for DCB testing was selected as 60 mm which was prepared by inserting a Teflon sheet of 50-micron (μm) thickness between the 4th and 5th plies. Lastly, aluminium blocks were placed on both sides of the pre-notch to apply loading, as illustrated in Figure 1(b).

3 – EXPERIMENTAL SETUP

The DCB test setup is displayed in Figure 2(a). The test was performed using a 10 kN Instron load frame at rate of 2 mm/min. The aluminium blocks were constrained by pins which allowed rotation of the samples (see Figure 2(b)), as displacement increased. The initial crack / delamination length (a_0) was set at 60 mm. As the load increased, the crack started to propagate which is referred as Δa. The successful testing samples should ensure the propagation of the crack within the interface without migrating into the adjacent layers (more discussion in Section 4). As such, the crack was measured until 10 mm, beyond which some specimens exhibited crack propagation through veneers instead of within the

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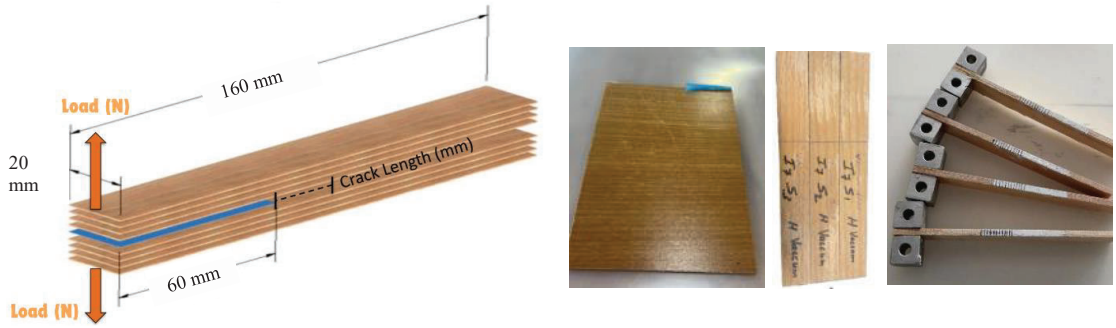
interface. The mode I strain energy release rate or fracture toughness, G_I was calculated from Eq. (1).

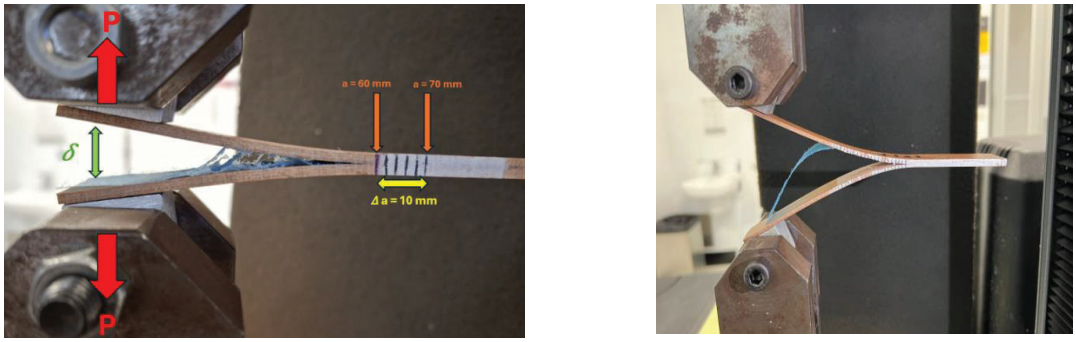
$$G_I = \frac{3P\delta}{2b(a+|\Delta|)} \quad (1)$$

where, P = resultant load, δ = pin displacement, b = specimen width and $a = a_0 + \Delta a$ = total delamination length. The correction factor Δ is the intercept of the $\left(\frac{\delta}{P}\right)^{(1/3)}$ vs Δa plot. The P, δ and Δa values were obtained from the experiments. The critical mode I strain energy release rate G_{Ic} can be calculated at the point of crack initiation, i.e., when $\Delta a = 0$.



(a) (b)

Figure 1(a) Sample dimensions for DCB testing (b) Final samples



(a) (b)

Figure 2 (a) Test setup (b) Successful failure samples

4 – RESULTS

4.1 BEECH VS OAK (TWO HARDWOOD SPECIES)

Figure 3 compares the load-displacement and mode I fracture strain energy release rate between European beech and Tasmanian oak. Both are hardwood species and grows in central Europe and Tasmania (and some part of Victoria), respectively. European beech properties are considered as benchmark and taken from another study by the same authors [8]. While comparing the Tasmanian oak against the benchmark species, similar behaviour in terms of load – displacement plots under mode I fracture testing is observed. This is due to their similar mechanical properties, e.g., the modulus of elasticity of the seasoned beech vs oak is approximately 15 and 17 GPa, respectively [21, 22]. Both seasoned oak and beech have a bending strength of 110 MPa [21, 22]. It can be noted here that only two samples were tested for Tasmanian oak, since the third sample broke prematurely due to poor manufacturing.

The average initial strain energy (initiation of crack) of beech and oak were 598.54 (± 22.05) and 498.89 (± 11.89) J/m^2, respectively. Therefore, oak yielded 83% of the initial strain energy of beech. However, for oak the strain energy remained almost linear along the crack length (as crack propagates from 0 to 8 mm), as shown in Figure 3(b). In contrast, slightly increasing trend in mode I strain energy is evident for beech. This was possibly due to the fibre bridging, indicating slightly superior bonding between beech plies.

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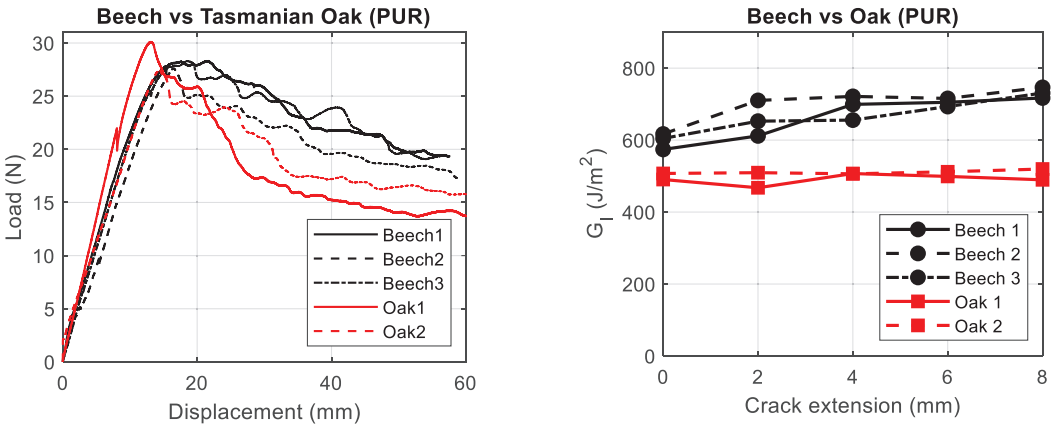
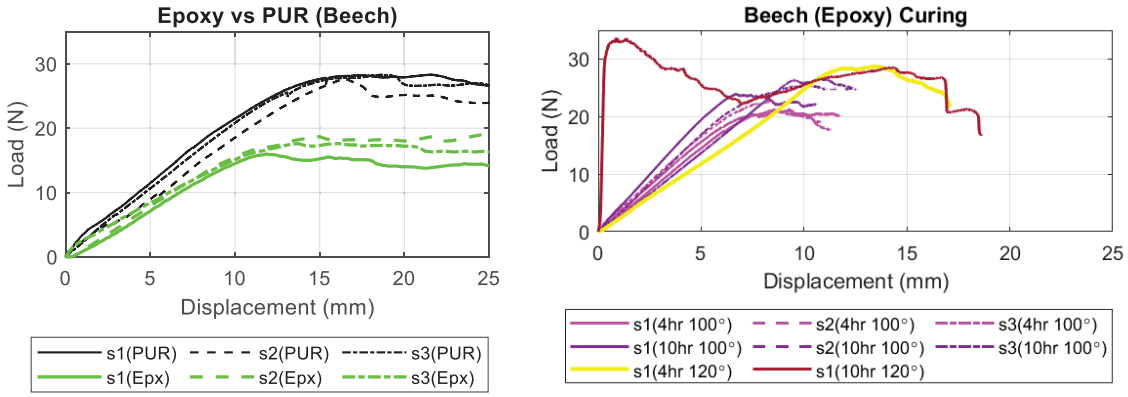


(a) (b)

Figure 3. Comparing European beech vs Tasmanian oak, (a) Load vs displacement, (b) Mode I strain energy release rate (R-curve)



(a) Epoxy (ambient cured) vs PUR (b) Various curing conditions (epoxy-Beech)

Figure 4. Exhibiting effect of adhesive and curing condition of epoxy on the load-displacement behaviour for mode I test

4.2 EFFECT OF ADHESIVE (EPOXY VS PUR)

This section compares interface properties of beech laminates when bonded using epoxy under various curing conditions. At first, the bio-epoxy based beech laminates, cured under ambient, condition is compared against the benchmark value, i.e., beech-PUR laminates. Figure 4(a) depicts the load-displacement behaviour of the bio-epoxy vs PUR based beech laminates. As indicated, the behaviour is similar in both cases, albeit with a slightly lower slope in the elastic region and lower ultimate load in case of bio-epoxy based laminates. Nevertheless, the plateau at the ultimate load is visible in both cases. When the curing conditions for epoxy-based beech laminates were varied by duration and temperature, brittle failures were observed (Figure 4(b)). This brittleness can be due to the loss of moisture in wood veneers which makes wood act in a brittle manner.

It can also be noteworthy to mention that only one sample was successfully tested when the epoxy-beech system was cured at 120°C due to the propagation of crack in the adjacent layers. For successful testing, the crack needs to propagate along the interface, as displayed in green line in Figure 5(a). For the unsuccessful samples, the crack migrated out of the initial interface (indicated as Zone B in Figure 5(b)). Although this indicates superior bonding between interfaces, it affects the estimation of mode I strain energy release rate. Another anomaly can be observed for the sample cured at 120°C for 10 hours. The slope of the load-displacement curve was unusually steep for this sample due to the melting of the Teflon insert (denoted as Zone A in Figure 5(b)).

Figure 6 represents the mode I strain energy release rate of the epoxy-beech samples, cured under various curing conditions and compared against the benchmark beech-PUR system. The samples pressed at 120°C exhibited the highest initial strain energy release rates of approximately 486 and 495 J/m², respectively, for 4 and 10 hour curing, indicating superior fracture resistance during the onset of crack propagation. These high values suggest that higher temperatures facilitate more complete cross-linking in the bio-epoxy, leading to improved bonding at the epoxy-beech interface. The higher cross-linking density creates a strong adhesive bond that provides improved resistance to crack initiation.

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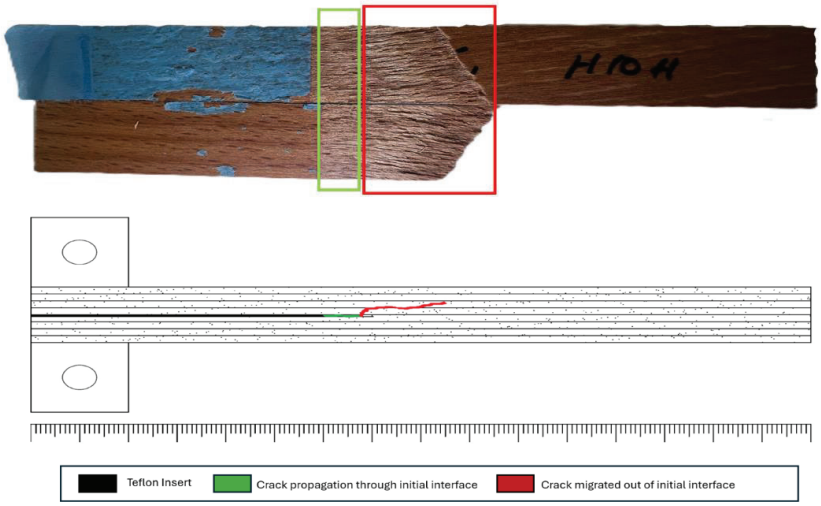
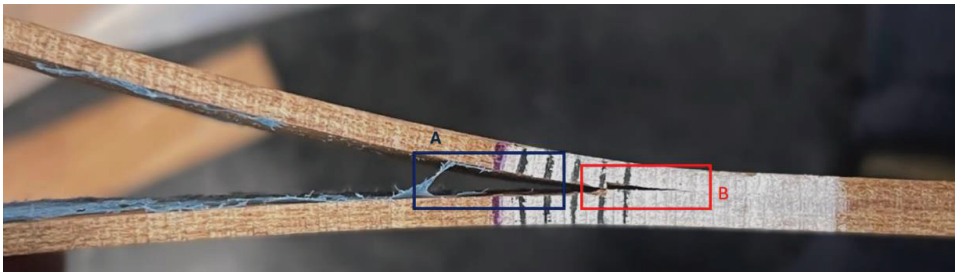


(a) Successful samples cured at 120°C



(b) Unuccessful samples cured at 120°C for 10 hours

Figure 5. Post-mortem examination of beech-epoxy sample cured at 120°C

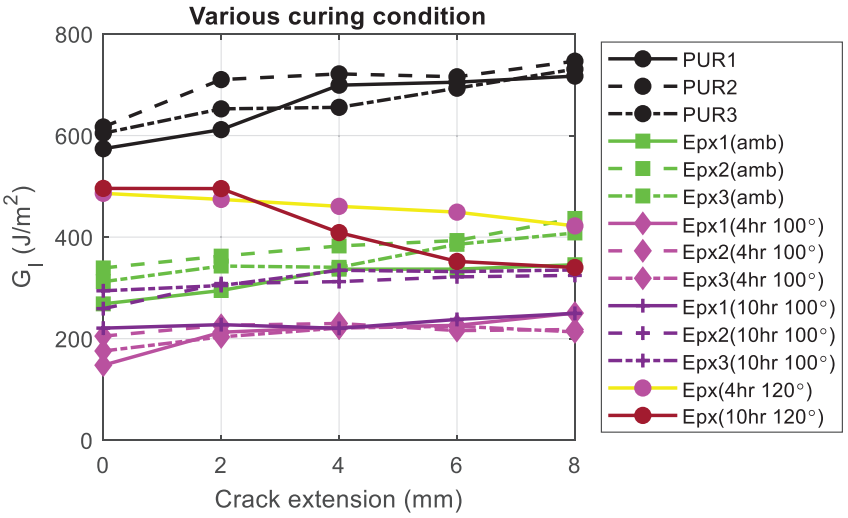


Figure 6. Exhibiting effect of adhesive and curing condition of epoxy on the mode I strain energy release rate (R-curve)

Decreasing energy values are a strong indication that the interface crack has migrated into the wood veneers. The fracture energy of wood is lower compared to typical resin systems.

At 100°C, the influence of pressing time becomes more apparent. Increasing the pressing time from 4 to 10 hours significantly enhances the strain energy release rate from ~176 J/m² to ~258 J/m² at the onset of crack propagation. This result demonstrates that at moderate temperatures,

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the bio-epoxy requires more time to fully cure, as the extended curing time leads to more complete cross-linking, increasing the resin's fracture toughness. The data shows that 100°C can be a practical compromise between achieving good mechanical properties and preventing excessive thermal degradation, especially when longer curing times are employed.

4.3 BEECH VS HOOP PINE (HARDWOOD VS SOFTWOOD)

Based on results obtained from Section 4.2, curing temperature of 100°C was considered for determining mode I fracture properties of hoop pine. Figure 7 presents the load-displacement curve of hoop pine subjected to mode I fracture testing and compared against the beech-epoxy system. As observed from the figure, effect of curing duration is not prominent for pine compared to beech. The maximum load of the pine is also lower than beech. A steeper slope is observed for heat cured samples (both beech and pine) compared to their ambient counterpart due to loss of moisture in timber. Similar to beech, pine also exhibited brittle failure.

The bonding between the hoop pine plies using epoxy was found to be insufficient that led to the delamination of the layers or crack migration, as illustrated in Figure 8. Therefore, mode I fracture properties cannot be determined for hoop pine. Future study will focus on detail investigations on hoop pine to propose an appropriate manufacturing technique, test setup and post-analysis method to characterise its mode I fracture properties.

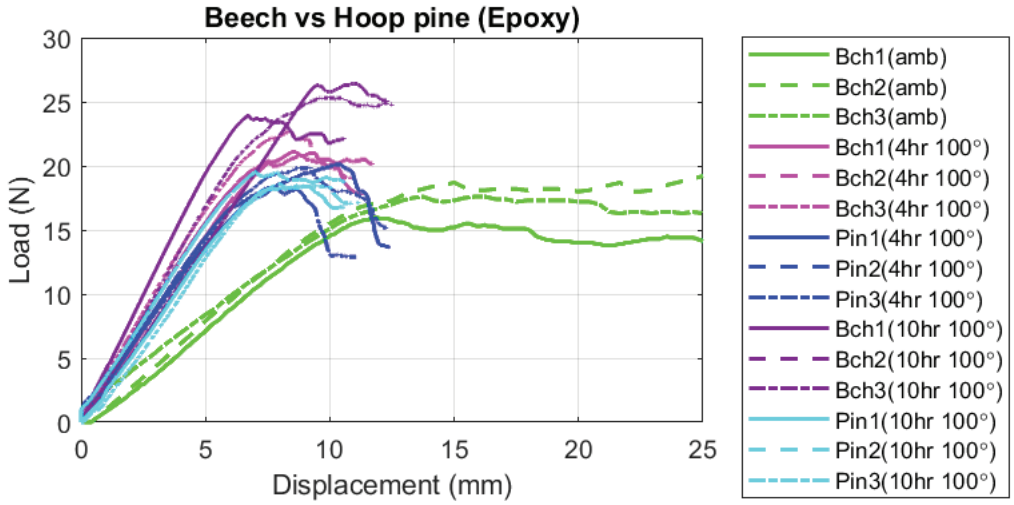
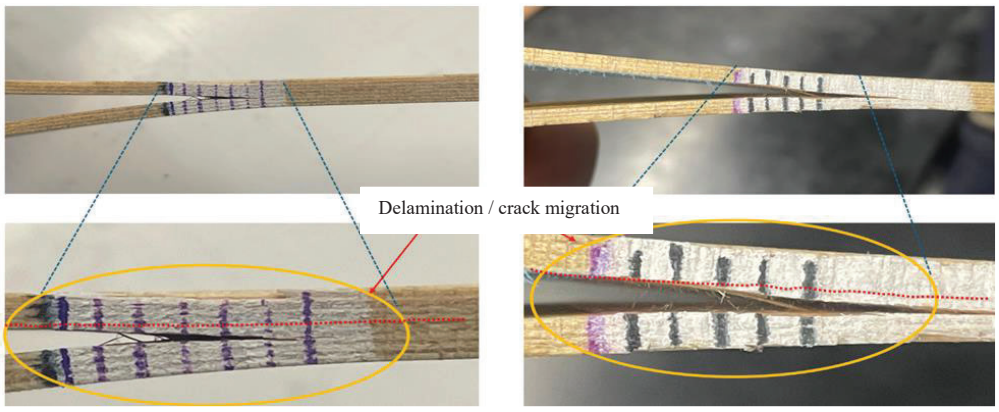


Figure 7. Exhibiting effect of adhesive and curing condition of epoxy on the mode I strain energy release rate (R-curve)



(a) Cured at 100°C for 4 hours (b) Cured at 100°C for 10 hours

Figure 8. Failure for hoop pine tested samples

4.4 COMPARISON

Figure 9 shows the load-displacement vs crack length graph of all the samples tested above. Only one sample per group is plotted for comparison. The effect of adhesive and curing duration are evident from the figure. Crack initiates at higher displacement, around 15 mm, for the PUR and ambiently cured epoxy-based timber

laminates. Beech veneers bonded with epoxy and cured at 120°C also exhibited higher displacement at which crack started to propagate. Crack started to propagate at much lower displacement values when the epoxy-based timber laminates (both beech and pine) are cured at 100°C, irrespective of their curing duration. This, again, indicates that the temperature has a greater effect on the mode I fracture properties when the curing duration is less than 10 hours.

The Col. (5) and (6) list the critical mode I strain energy release rate (G_{Ic}) and compare against the benchmark value of the beech-PUR system. As outlined in Col. (6) the Tasmanian oak – PUR system and European beech – epoxy system cured at 120°C attained more than 80% of the G_{Ic} value related to the benchmark system.

Literature related to the assessment of mode I fracture toughness of timber-PUR or timber-epoxy system for veneers is limited. However, some studies focused on the mode I fracture properties of sawn wood made from various species. Radiata pine (softwood) bonded using PUR reported to have mode I interlaminar fracture toughness of 820 J/m^2 [16]. Sterley et al. reported mode I fracture toughness of 452 – 494 J/m^2 for Norway spruce (softwood) with density varied between 310 – 430 kg/m^3 for dry wood bonded with PUR. For green spruce, these values varied between 386 – 571 J/m^2. Crespo et al. [15] calculated mode I fracture toughness of Eucalyptus globulus (hardwood) with various density and obtained an mean value of 691 J/m^2 in terms of mode I interlaminar fracture toughness. Xavier et al. [17] used epoxy to bond maritime pine and achieved mode I interlaminar fracture toughness of 354 J/m^2. Based on these previous studies, it can be concluded that the mode I fracture toughness achieved in this study for hardwood with PUR and epoxy are within the ranges of the values reported in literature.

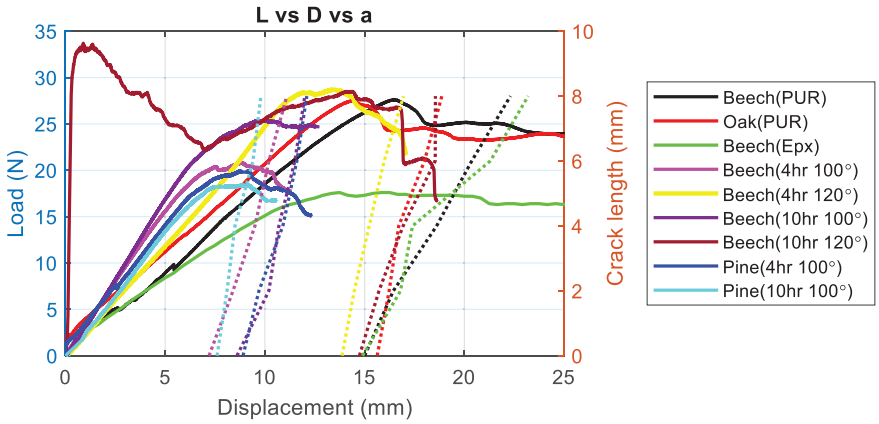


Figure 9. Exhibiting effect of adhesive and curing condition of epoxy on the mode I strain energy release rate (R-curve)

5 – CONCLUSION

This study focused on assessing the interface properties of three species (two hardwood and one softwood) using two different adhesive systems – polyurethane and bio-epoxy. Mode I fracture tests were performed to assess their interface properties. The benchmark species was European beech which is a hardwood species and was compared against Tasmanian oak and hoop pine that are Australian hardwood and softwood, respectively.

As per the results, European beech bonded with polyurethane attained the highest mode I fracture toughness with a mean magnitude of 598 J/m^2 with a standard deviation of 22.05 J/m^2. Tasmanian oak plies, bonded using polyurethane, also attained high fracture toughness of 498 J/m^2 which is 83% of the values of beech. Use of epoxy decreased the mode I fracture toughness of beech by almost 50%. However, increasing the curing temperature and duration was found to be effective to improve the mode I fracture properties of beech. A curing temperature of 120°C for 4 or 10 hours can increase the mode I fracture toughness by 58% and 62%, respectively, compared to its ambiently cured counterpart. When the curing temperature was set at 100°C for 4 and 10 hours, the fracture toughness values fell below the ones measured in ambient cured laminates. This indicates that longer curing duration is needed for 100°C.

For hoop pine, only 100°C was considered for curing temperature, since 120°C enhance interface properties significantly that led to crack migration, limiting the calculation of mode I fracture toughness. However, it was found that 4- or 10-hour curing duration was not sufficient for hoop pine, since it resulted pre-test delamination. Therefore, fracture properties cannot be determined. Further study will be conducted to determine fracture properties of hoop pine by optimising the curing condition.

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