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AN EXPLORATORY STUDY ON MIXED-MODE FRACTURE AND STRAIN DISTRIBUTION NEAR A CRACK TIP OF ADHESIVELY-LAMINATED WOOD SPECIMENS USING THE MODIFIED ARCON FIXTURE AND DIGITAL IMAGE CORRELATION

Zizhen Gao[1], Meng Gong[2], Ling Li[3], Mohsen Mohammadi[4]

ABSTRACT: Glue-laminated lumber-based mass timber products, such as glue-laminated timber (GLT), have been widely used in construction. This study was aimed at understanding the mixed mode fracture behaviour of a bond-line of GLT using the modified Arcon fixture and digital image correlation (DIC) technique. The laminated wood specimens used were made of white spruce (*Picea glauca*), as the laminations, and structural adhesives, say emulsion polymer isocyanates (EPI) and polyurethanes (PUR). The modified Arcan fixture was employed to implement mixed mode stress conditions at different angles. The effects of adhesive type on the mixed mode fracture behaviour of a bond-line of laminated wood specimens were examined. In addition, the strain distribution near the crack tip of a bond-line was illustrated using the DIC system. The results showed that the critical mode I and mode II stress intensity factors, K_{Ic} and K_{IIc}, were 0.48 MPa√m and 0.72 MPa√m for the specimens made of white spruce and EPI, respectively, while those were 0.73 MPa√m and 0.90 MPa√m for the specimens made of white spruce and PUR, respectively. In addition, the mixed mode fracture criteria for the EPI and PUR bond-lines were proposed, resulting in a good correlation with the experimental data.

KEYWORDS: Glue-laminated specimen, Bond-line, Mixed mode fracture, Arcan test, Digital image correlation

1 INTRODUCTION

Adhesively bonding represents the most common joining technique in modern engineered wood products (EWPs). Lumber-based mass timber products are commonly made with an adhesive(s), such as glue-laminated timber (GLT) and cross-laminated timber (CLT), which have been widely used in construction [1, 2]. In these adhesively laminated products, the mechanical performance of a bond-line(s) plays a critical role in the structural behaviour of a wood product, and furthermore governs the safety and durability of a timber structure. Therefore, understanding of the mechanical performance of a bond-line(s) is of great importance in use of these mass timber products. Fracture characterized as the formation of new surfaces in wood is one of the most important properties mass timber products. It should be emphasized that the bond joints usually are subjected to mixed-mode loading [3]. Therefore, a deep understanding of the fracture behaviour of an adhesively bonded joint under a given load, in particularly under mixed-mode loading conditions, is no doubt required.

There are many studies in the measurement of mixed mode fracture toughness of EWPs. *Mall* et al. investigated the mixed mode fracture toughness of eastern red spruce (*Pieca rubens*) using the single edge notch and centre crack specimens, in a nominal equilibrium moisture content of 12% (±1%), with various crack inclinations in the tangential-longitudinal (TL) plane of wood [4]. Their results indicated that there was a definite interaction between two failure stress intensity factors (K_I and K_{II}) during the mixed mode fracture in wood [4]. *Jernkvist* tested the mixed mode fracture performance of Norway spruce (*Picea abies*), with moisture content of 12.2%, in the radial-longitudinal (RL) plane of wood and derived a criterion for predicting the mixed mode fracture toughness of wood [5, 6]. Their results showed that onset of mixed mode fracture could be predicted with a simple fracture criterion in the crack system [5, 6]. *Moura* et al. obtained a mixed mode fracture criterion for the maritime pine (*Pinus pinaster*), for the moisture content of 12.3%, based on the critical fracture energy from a modified mixed mode bending test [7]. The mixed mode fracture toughness (K_c) of a bond-line of phenol resorcinol formaldehyde (PRF) resin and a one-component polyurethane (PUR) adhesive with European beech (*Fagus sylvatica*) wood adherends at the relative humidities (RH) of 50%, 65%, and 95% of the surrounding air were examined by *Ammann* et al. [8]. Their results indicated that K_c of the specimens made of either adhesive increased with increasing shear stresses, and the PUR bond-line generally showed a lower K_c than the PRF one in dry climate [8]. It is well known that the fracture energy under mode-II loading is different from that under mode-I loading in adhesively bonded joints [9].

[1] Zizhen Gao, University of New Brunswick, Canada, zz.gao@unb.ca
[2] Meng Gong, University of New Brunswick, Canada, mgong@unb.ca
[3] Ling Li, University of Maine, USA, ling.li@maine.edu
[4] Mohsen Mohammadi, University of New Brunswick, Canada, mohsen.mohammadi@unb.ca

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For the situation under the mixed-mode loading, there is an interaction between the two fracture modes, requiring to find a relationship between mode-I and mode-II stress intensity factors [4-6, 9].

The Arcan test was first proposed by *Arcan* et al. [10] with an attempt to produce uniform plane stress state in the test section of a specimen. The Arcan testing configuration has been proved very successful for testing and evaluating mixed mode fracture performance of different materials, including wood, plastic, composites and mental [8, 9, 11, 12]. One of the advantages of the Arcan test is that it allows mode I, mode II, and almost any combination of mode-I and mode-II loading to be tested with the same test specimen configuration [9].

Digital image correlation (DIC) technique is a popular non-contact method for measuring the distribution of displacement and strain on the surface of a specimen under loading [13]. As the development of DIC method and computer technology, researchers have widely employed it to evaluate the fracture performance of a material [14, 15].

This study was aimed at understanding the mixed mode fracture behaviour of a bond-line of laminated solid wood products with help of a modified Arcan testing setup and a DIC system.

2 FRACTURE MECHANICS

There are three types of cracks, termed Modes I, II, and III as illustrated in Fig. 1 [16]. The Linear Elastic Fracture Mechanics (LEFM) is deemed to be a useful tool for investigating the cracks in wood and wood products. The strain energy release rate (G) and stress intensity factor (K) are two main indexes for evaluating the fracture behavior of a material [16].

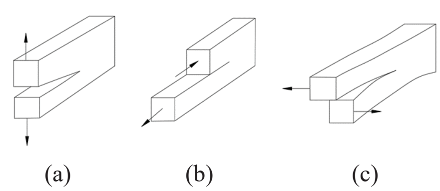

Figure 1: *Three fracture modes: (a) Mode I – Tension; (b) Mode II – In-plane shear; (c) Mode III – Out-of-plane shear.*

K_I and K_{II} for through the thickness edge crack in a finite body subjected to uniform stress at edges are given in Eqs. 1 and 2 [17]:

$$K_I = \sigma\sqrt{\pi a} f_1(\frac{a}{w}) \quad (1)$$

$$K_{II} = \sigma\sqrt{\pi a} f_2\left(\frac{a}{w}\right) \quad (2)$$

K_I and K_{II} for such stress condition in a Arcan specimen can be calculated using Eqs. 3 and 4 [11, 12]:

$$K_I = f_I(\frac{a}{w})\frac{P}{wt}\sqrt{\pi a} \quad (3)$$

$$K_{II} = f_{II}\left(\frac{a}{w}\right)\frac{P}{wt}\sqrt{\pi a} \quad (4)$$

Where, P is the critical load on the specimen for crack propagation; t is the thickness; w is the width, and a is the initial crack length.

3 MATERIALS AND METHOD

3.1 MATERIALS

White spruce (*Picea glauca*) lumber of a thickness of 38mm was obtained from a sawmill in New Brunswick, Canada, which were stored in a conditioning chamber with a relative humidity (RH) of 65% and a temperature of 20 C° for two months. The physical properties of the lumber used after conditioning were tested in a separate study by the authors, which are given in Table 1. Two types of adhesives were used, two-component emulsion polymer isocyanates (EPI) and one-component polyurethanes (PUR), which were obtained from Ashland Inc. and Lepage Inc. respectively.

Table 1: *Elasticity and physical properties of lumbers*

Property	Mean (COV)
Density (g/cm^3)	0.38 (5.24%)
MC (%)	13.73 (1.13%)
E_L (MPa)	9932 (9.10%)
E_R (MPa)	517 (14.67%)
E_T (MPa)	221 (12.14%)
ν_{LR}	0.41 (16.7%)
ν_{LT}	0.51 (10.52%)

3.2 SPECIMENS

The EPI and PUR specimens were made using EPI and PUR as the adhesives with a spread rate of 220 g/m^2, respectively, while white spruce lumber was used as the adherend for both EPI and PUR specimens. The specimens used were processed to have a butterfly shape, Figure 2, to fit the modified Arcan fixture. An initial crack with a length of 10 mm was carefully made by placing a 0.1-mm-thick Teflon sheet between laminations after spreading adhesives. A speckle pattern with high contrast was applied to the surface of the specimens for DIC analysis, and the speckle size was 0.2 mm.

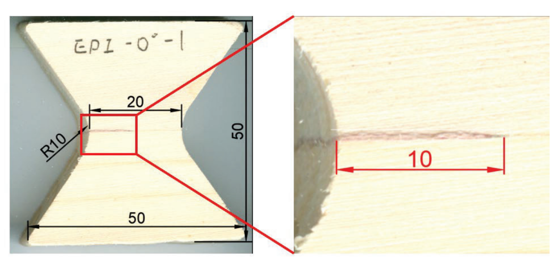

Figure 2: *The specimen used for Arcan test*

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3.3 TESTING METHOD

The mixed mode fracture criteria of a bond-line were determined using the butterfly-shape specimens. To achieve this, seven angles were used in the modified Arcan fixture to generate the mixed mode stress conditions, Figure 3, ranging from 0 (Mode I) to 90 (Mode II) degrees with an interval of 15 degrees.

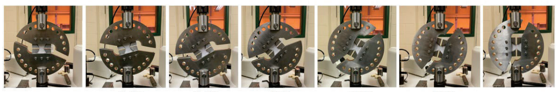


Figure 3: *Experimental setups of the Arcan fixture at seven angles.*

Two cameras were set up in the front of a specimen to capture the images from the DIC system, Figure 4. The image logging frequency of two cameras was set at 2Hz (2 images per second), which was the same as the data logging frequency of the mechanical testing machine. The load was applied at a rate of 0.5mm/min and the fracture loads were recorded. All the tests were carried out using an Instron testing machine (Model: 3367). A 3D-DIC system and software by the Correlated Solutions was used to analyse the images and calculate the strain distribution.

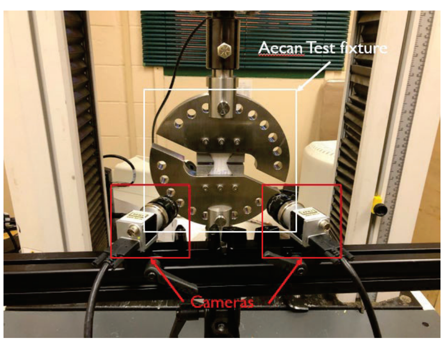


Figure 4: *Testing setup mounted with a DIC system.*

4 RESULTS AND DISCUSSION

Figure 5 gives the critical load (P_c) of EPI and PUR specimens loaded at different angles. It can be found that the P_c of PUR specimens are overall higher than those of EPI ones. For both EPI and PUR specimens, with the loading angle increasing, the P_c increases. The P_c under pure shear stress has the highest value. It is worth to note that, as airdry wood can be approximately treated as an elastic material, the process of crack propagation is usually instantaneous. Therefore, the peak load was recorded as the P_c in this study.

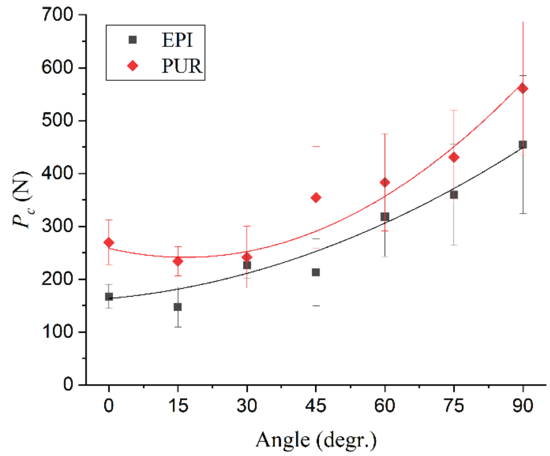
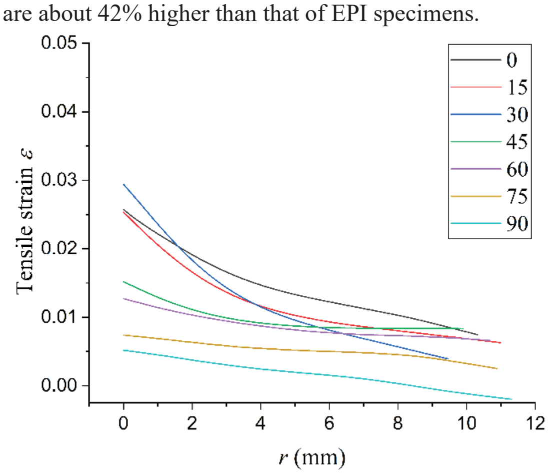
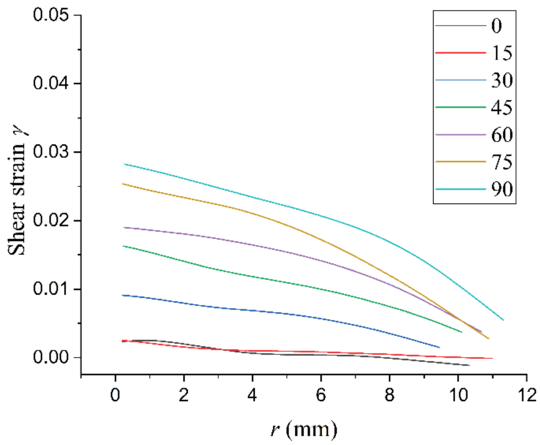


Figure 5: *Critical Loads at different angles.*

The critical strain distribution along a bond line means the strain distribution at the point at which a crack starts propagating. The critical strain distributions of EPI and PUR specimens are plotted in Figures 6 and 7, respectively. The results showed that the average tensile strain (ε_c) of both EPI and PUR specimens decreased with the loading angle increasing, while the average shear strain (γ_c) increased. In addition, for both EPI and PUR specimens, tensile strain is more concentrated at the crack tip than shear strain. Figure 8 gives the relationship between the critical tensile strain and critical shear strain at crack tips. It can be found that both critical tensile strain and shear strain of PUR specimens are overall larger than those of EPI specimens, which reflects the difference in P_c between these two types of specimens. Moreover, Figure 8 shows that with increasing the loading angle, the changes in tensile strain and shear strain are not linear, suggesting that the mixed mode facture criterion of a bond-line is a critical index for predicting the fracture of an adhesively-laminated wood product subjected to a mixed loading condition. In addition, under the pure tension or shear loading, both ε_c and γ_c of PUR specimens are about 42% higher than that of EPI specimens.

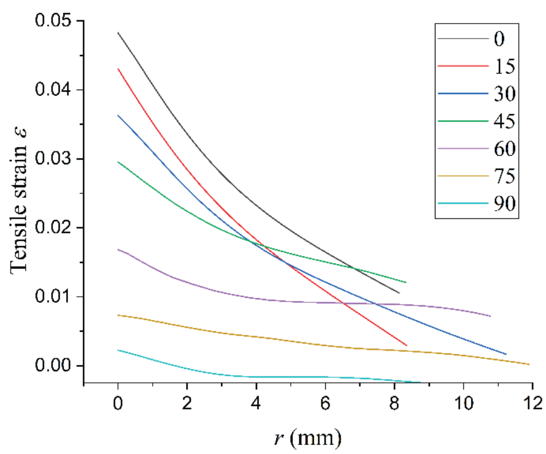


(a) Average tensile strain distribution

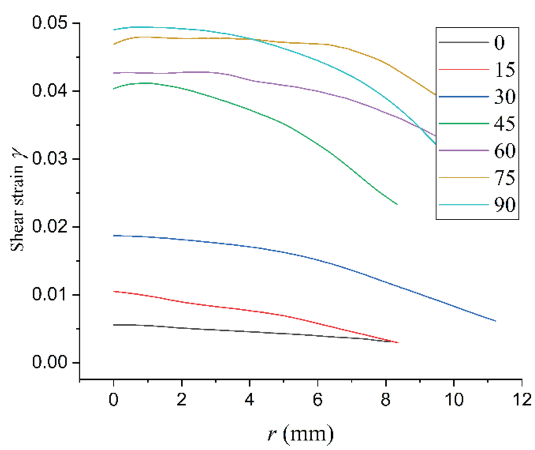


(b) Average shear strain distribution

Figure 6: *Average critical strain distributions along the bond-lines of EPI specimens under the criterial load.*



(a) Average tensile strain distributions



(b) Average shear strain distributions

Figure 7: *Average strain distributions along the bond-lines of PUR specimens under criterial load.*

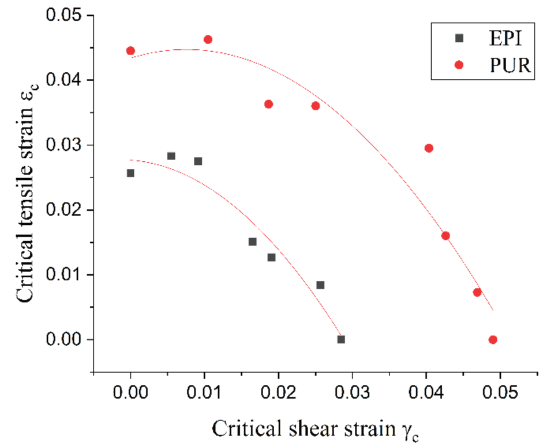


Figure 8: *Relationship between the critical tensile strain and shear strain at the crack tips of two-type specimens.*

According to Equations (3) and (4), the K_I and K_{II} represent the strength of the stress singularity that occurs at a sharp crack tip. The K_I or K_{II} is a function of the specimen geometry, applied load and crack length. The nondimensional stress intensity factors (e.g., geometrical factors, *f(a/w)*) of the modified Arcan specimens for mode I and mode II can be obtained by the finite element analysis (FEA) [18, 19], Figure 9. The geometrical factor functions for Mode I and Mode II fracture were determined in this study by using the least square fitting method, which are given in Equation (5) and (6).

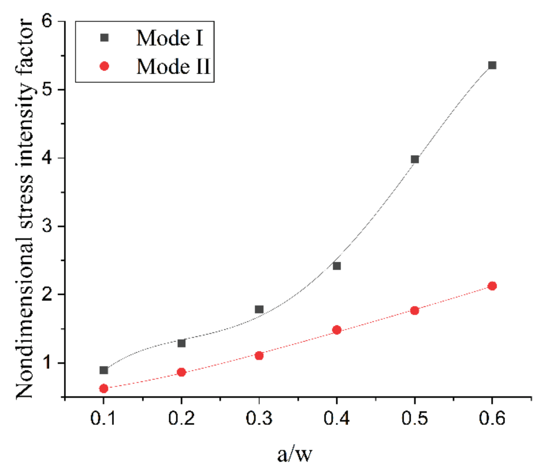


Figure 9: *Non-dimensional stress intensity factors for Mode I and Mode II fracture of the specimens tested using the modified Arcan fixture.*

$$f_I\left(\frac{a}{w}\right) = -237.04\left(\frac{a}{w}\right)^4 + 339.84\left(\frac{a}{w}\right)^3 - 150.15\left(\frac{a}{w}\right)^2 + 29.33\left(\frac{a}{w}\right) - 0.863 \quad (5)$$

$$f_{II}\left(\frac{a}{w}\right) = 7.42\left(\frac{a}{w}\right)^4 - 13.17\left(\frac{a}{w}\right)^3 + 9.26\left(\frac{a}{w}\right)^2 + 0.25\left(\frac{a}{w}\right) + 0.5223 \quad (6)$$

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Tables 2 and 3 summarize the results of failure stress intensity factors K_I and K_{II}, obtained from all specimens at different loading angles. The critical mode I and mode II stress intensity factors, K_{Ic} and K_{IIc}, for EPI specimens are 0.48 MPa√m and 0.72 MPa√m, respectively, while those for specimens are 0.73 MPa√m and 0.90 MPa√m. The fracture mechanics parameters of the bond-lines of both EPI and PUR specimens made with white spruce have not yet been reported. However, the K_{Ic} and K_{IIc} in this study are comparable with the results from *Ammann's* study, in which the K_{Ic} and K_{IIc} of the bond-lines of the specimens made of PUR adhesive and European beech wood were 0.75 MPa√m and 1.85 MPa√m, respectively [8]. In addition, K_{Ic} and KI_{Ic} of the specimens made of solid Norway spruce wood, which were reported by *Jernkvist* [6], were 0.58 MPa√m and 1.52 MPa√m, respectively.

Table 2: *Failure stress intensity factors K_I and K_{II} of EPI.*

Angle	K_I (MPa√m)		K_{II} (MPa√m)	
	Mean	COV	Mean	COV
0	0.48	0.14	0.00	0.00
15	0.42	0.19	0.06	0.22
30	0.50	0.11	0.16	0.11
45	0.43	0.23	0.23	0.25
60	0.42	0.24	0.40	0.23
75	0.27	0.27	0.53	0.27
90	0.00	0.00	0.72	0.31

Table 3: *Failure stress intensity factors KI and KII of PUR.*

Angle	K_I (MPa√m)		K_{II} (MPa√m)	
	Mean	COV	Mean	COV
0	0.73	0.11	0.00	0.00
15	0.67	0.19	0.09	0.16
30	0.62	0.28	0.19	0.26
45	0.64	0.26	0.36	0.26
60	0.53	0.21	0.49	0.22
75	0.32	0.15	0.64	0.17
90	0.00	0.00	0.90	0.17

To examine the interaction between K_I and K_{II} of EPI and PUR specimens under different loading angles, all the data are plotted in Figure 10. This figure indicates that the trend of relationship between K_I and K_{II}, which defines the tensile stress and shear stress distributions near a crack tip, is similar to that between ε_c and γ_c.

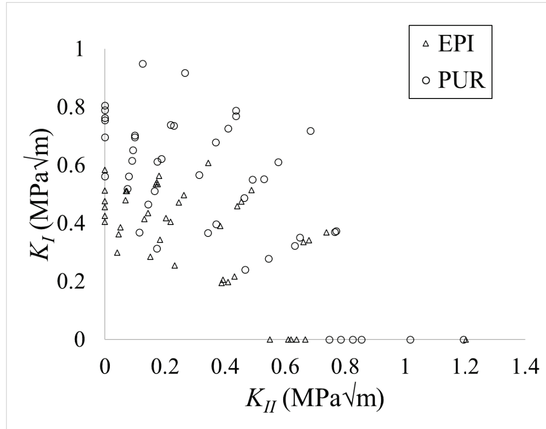

Figure 10: *Relationship between K_I and K_{II}.*

For the situation under a mixed-mode loading, there is an interaction between the two fracture modes, calling for investigating the relationship between K_I and K_{II} [20]. The mixed fracture criterion is generally proposed in Equation (7) [6]:

$$\frac{K_I}{K_{Ic}} + \left|\frac{K_{II}}{K_{IIc}}\right|^n = 1 \quad (7)$$

The subject of the mixed mode fracture in wood-based materials was first studied by *Wu* [21], who found that Equation (7) could well describe the interaction between K_I and K_{II} of balsa wood (*Ochroma pyranidale*) when n=2. *Mall* et al. [4] compared several mixed mode fracture criteria and discovered that *Wu*'s criterion was also applicable to eastern red spruce (*Pieca rubens*). *Jernkvist* found, using the least square fitting method based on their experimental data, that Equation (7) could be used as the fracture criterion of Norway spruce when n=2.2 [6]. The values of n in Equation (7) for the fracture of EPI bond line and PUR bond line could be obtained using the least square fitting method according to the data in Tables 2 and 3, and Figure 11. The fitting parameters are given in Table 4. The n values of the mixed mode fracture criterion for EPI and PUR are found to be 1.89 and 2.93, respectively, suggesting that the mixed mode fracture criterion of EPI bond line is similar to the clear softwood specimens such as red eastern spruce and Norway spruce [4, 6].

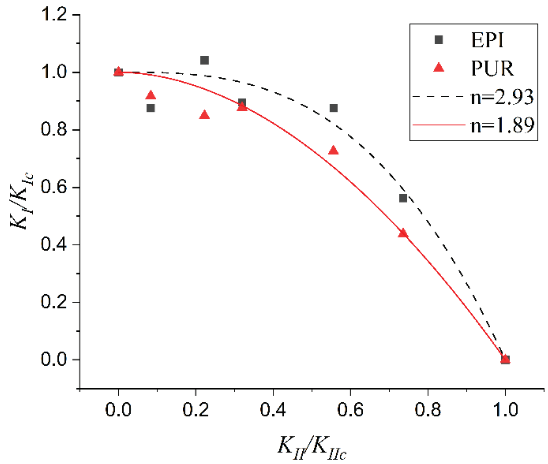

Figure 11: *Relationships between K_I/K_{Ic} and K_{II}/K_{IIc}.*

Table 4: *Fitting parameters of the relationship between K_I/K_{Ic} and K_{II}/K_{IIc}.*

	EPI specimen	PUR specimens
n	2.93	1.89
R-square	0.966	0.977
p-value	<0.0001	<0.0001

Figures 12 and 13 show the typical failure modes of EPI and PUR specimens. It was found that the crack propagation paths were similar between specimens, i.e., the crack propagation started from a crack tip and grew along the fibre direction of wood near a bond-line. Despite the crack propagation started from the glue-line, the crack path was totally along the clear wood, which means that, for both EPI and PUR specimens, the wood failure percentage were 100%.

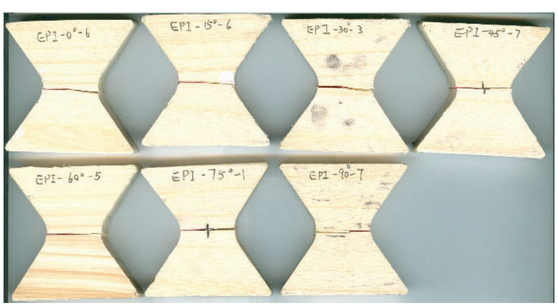

Figure 12: *Failure mode of EPI sample specimens.*

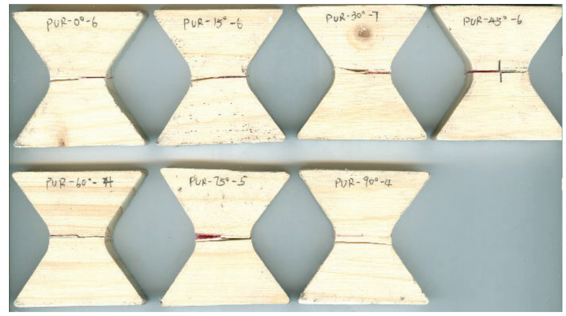

Figure 13: *Failure mode of sample PUR specimens.*

5 CONCLUSIONS

In this study, a modified Arcan testing setup equipped with a 3D-DIC system were employed to examine the mixed fracture properties of a bond-line of the wood products bonded with EPI and PUR adhesives. The strain distributions and critical strains of each specimen were obtained using the DIC system. Based on experimental observations, data analysis and above discussion, the conclusions could be drawn as follows:

(1) Under the pure tension or shear loading, both ε_c and γ_c of PUR specimens were 42% higher than those of EPI ones, and tensile strain was more concentrated at the crack tip than shear strain.

(2) The K_{Ic} and K_{IIc} of the bond-line of EPI specimens were 0.48 MPa√m and 0.72 MPa√m, respectively, while those for PUR specimens were 0.73 MPa√m and 0.90 MPa√m, respectively.

(3) The n of the mixed mode fracture criterion for EPI and PUR specimens were 1.89 and 2.93, respectively.

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