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Research Article

Adhesive Through-Reinforcement Improves the Fracture Toughness of a Laminated Birch Wood Composite

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In this paper we test the hypothesis that adhesive through-reinforcement in combination with glass-fibre reinforcement of adhesive bond lines will significantly improve the fracture toughness of a laminated birch wood composite. We test this hypothesis using a model composite consisting of perforated veneer that allowed a polyurethane adhesive to penetrate and reinforce veneers within the composite. Model composite specimens were tested for mode I fracture properties, and scanning electron microscopy was used to examine the microstructure of fracture surfaces. Our results clearly show that through-reinforcement, and also reinforcing adhesive bond lines with glass-fibre, significantly improved fracture toughness of the birch wood composite. Our results also indicate that improvements in fracture toughness depended on the level of reinforcement. Improvements in fracture toughness were related to the ability of the reinforcement to arrest crack development during fracture testing and the fibre bridging effect of glass-fibre in adhesive bond lines. We conclude that through-reinforcement is an effective way of improving the fracture toughness of laminated wood composites, but further research is needed to develop practical ways of creating such reinforcement in composites that more closely resemble commercial products.

1. Introduction

Fracture toughness is an indicator of the stress required to propagate a preexisting flaw and is a critical property for materials such as laminated composites used in demanding structural applications [1]. Delamination of laminated composites reduces their stiffness and strength and can lead to loss of structural integrity [2]. Hence, there is significant interest in improving the fracture toughness of laminated composites, particularly those used for aircraft construction [1, 3]. Modern high performance aircraft uses a range of components made from laminated carbon-fibre/epoxy composites [4], but in less demanding aerospace applications the laminated wood composite plywood is still used (Euro Plywood 2016) [5]. Plywood consists of thin layers of wood veneer that are glued together, with adjacent layers having their wood grain rotated up to 90 degrees to one another [6]. The glue lines of plywood and also other laminated wood composites such as laminated veneer lumber (LVL) and glue-laminated lumber (glulam) often contain flaws and they can fail by delamination [7]. Hence, there has also been interest in improving their fracture toughness [8].

The susceptibility of laminated composites to delamination depends on a variety of intrinsic and extrinsic factors, but the lack of reinforcement of adhesive bond lines is a fundamental reason why cracks propagate between laminae [4]. Therefore, one obvious route to increasing the fracture toughness of laminated composites is to provide such reinforcement. For example, numerous studies have shown that the susceptibility of laminated composites to delamination can be reduced by reinforcing adhesive bond lines with fibres that act as bridges to inhibit crack opening [9]. Wegst et al. [10] reviewed this approach, and others used to improve fracture toughness of materials. Another approach

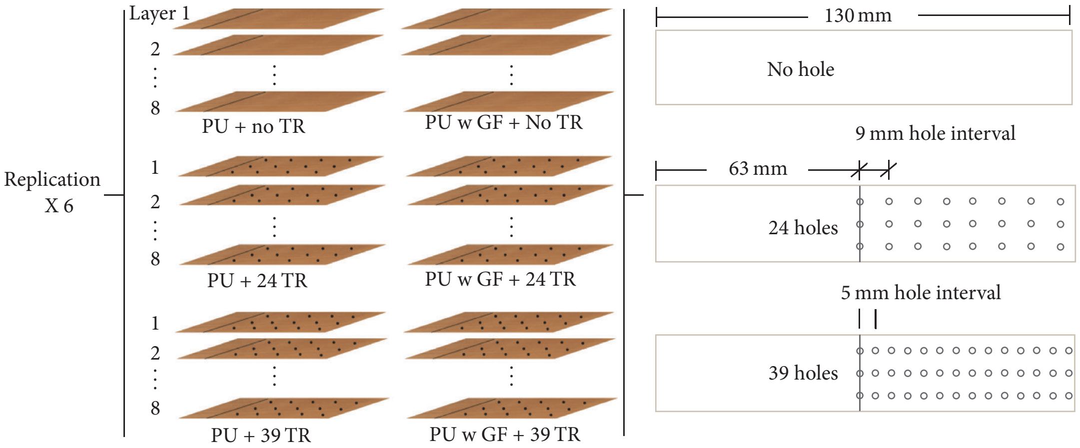


Figure 1: Preparation of laminated birch wood composite specimens with two levels of through-reinforcement (TR) of laminae and polyurethane (PU) adhesive bond reinforcement with glass-fibre (GF).

to improving the fracture toughness of laminates, which we explore here, is to alter the geometry of the adhesive network to provide through-reinforcement across multiple laminae. Such an approach is related although not identical to those used to provide through-thickness reinforcement of advanced composites, for example, 3D-weaving, stitching, braiding, embroidery, tufting, and z-anchoring [3].

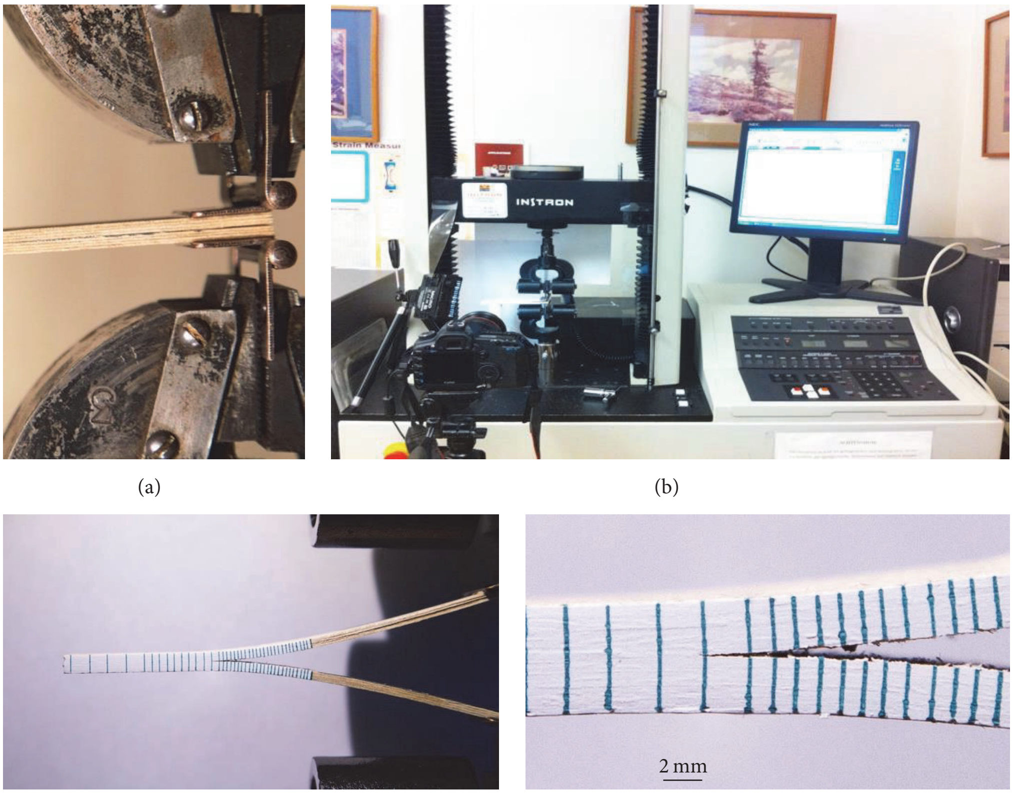
In this paper we test adhesive through-reinforcement across multiple laminae in combination with glass-fibre reinforcement of adhesive bond lines as a means of improving the fracture toughness of a model laminated birch wood composite. Our results demonstrate that the fracture toughness of the wood composite can be significantly improved as a result of the introduction of adhesive through-reinforcement. Further significant increases in fracture toughness occurred when glass-fibre was added to the adhesive.

2. Materials and Methods

2.1. Preparation of a Laminated Birch Wood Composite with Through-Reinforcement. Our main experiment examined the effect of adhesive through-reinforcement (two levels) and the effect of glass-fibre reinforcement of adhesive bond lines on different measures of fracture toughness of a model laminated birch wood composite (Figure 1). Two different types of samples were prepared: One contained a higher level of reinforcement than the other (39 Z-direction reinforcements versus 24 reinforcements). There was only one level of glass-fibre reinforcement of adhesive bond lines (5.5% w/w). Birch was chosen as the test substrate because composites made from this wood species were widely used for the manufacture of aircraft during WWII, and there is ongoing interest in using birch plywood for the construction of unmanned aerial vehicles (drones) [11, 12]. Eight birch wood veneer sheets were purchased from a retailer (ENE Wood Products Surrey, British Columbia, Canada) and stored in a conditioned room (20 ± 1°C and 65 ± 5% relative humidity) for 1 month to ensure they reached equilibrium moisture content and stable dimensions before the experiment.

Six different types of specimen were made, and there were six replications of each specimen type (Figure 1). Manufacture of specimens was as follows. Each specimen contained 8 veneer layers, individually grain matched and selected from 8 veneer sheets. Strips measuring 130 mm × 25 mm were cut from veneer sheets using a paper guillotine (Boston™ 2658). These dimensions were chosen because they are the same as those recommended by ASTM standard D5528-13 [13]. Veneer strips used for specimens with adhesive through-reinforcement were perforated with a high-speed dental drill (W&H® Trend WD-56) and a 1 mm diameter drill bit (Dentsply® TN burr) operating at 6000 rpm and 100 g/cm of torque. The drill produced accurately sized, smooth, cylindrical 1 mm diameter holes in each veneer strip. The 8 veneer strips used to make each laminated composite were placed in a customized mould to align them vertically, and all 8 strips were perforated together in the mould. Veneer for specimens with higher levels of adhesive through-reinforcement contained 39 holes (3 rows × 13 columns [density of through-reinforcement = 2.33/cm^2]) with a spacing of 5 mm (Figure 1). Veneer for specimens with lower levels of adhesive through-reinforcement contained 24 holes (3 rows × 8 columns [density of through-reinforcement = 1.43/cm^2]) with a spacing of 9 mm (Figure 1). Control specimens were not perforated.

A one-component polyurethane adhesive (Gorilla Glue Co., USA) was used to bond veneer strips. The glue was either used in an unmodified form or modified by the addition of 5.5% w/w milled (60 mesh) glass-fibre (Fiber-Tek®, Burnaby, BC, Canada). Adhesive (0.187 g ± 0.0005 g) was applied to each veneer strip using a syringe (BD® 1 mL syringe) and spread evenly across each veneer using a glass coverslip (Matsunami®). The *same amount* of adhesive was applied to perforated and unperforated veneer strips. Veneers were then laid up with their grain direction parallel to each other (like the commercial composite, laminated veneer lumber) to make specimens consisting of either perforated or unperforated veneer strips. A strip of aluminum foil measuring 63 mm × 25 mm was inserted into the end of



(a) (b) (c) (d)

Figure 2: Mode I (crack opening mode) fracture toughness testing of a laminated birch wood composite: (a) Hinges used to attach one end of a specimen to the two cross-heads; (b) universal tensile testing machine with attached computer, and also showing the position of the DSLR camera for measurement of crack propagation and crack length; (c) white coated edge of one side of a specimen with scale markers; (d) higher magnification image of (c) showing the position of a crack tip front.

the middle two veneer strips in each specimen to cover an area of 63 mm × 25 mm. This foil insert served as a crack initiator during fracture testing as recommended by ASTM D5528-13 [13]. Specimens were placed in a small laboratory press (Carver® hydraulic press 3912) and pressed at room temperature at 3 MPa for 8 minutes. The adhesive penetrated through the Z-direction holes in each veneer, creating adhesive through-reinforcement across multiple laminae [14]. No such reinforcement occurred in the unperforated veneers [14]. The resulting laminates were conditioned at 20 ± 1°C and 65 ± 5% r.h. for 7 days.

A second experiment examined the effects of different levels of adhesive through-reinforcement (0, 6, 12, 18, 51, and 66 holes) on the fracture toughness of a model laminated birch wood composite bonded with unmodified PU adhesive. This experiment sought to find the lower and upper limits for the ability of adhesive through-reinforcement to improve the fracture toughness of the birch wood composite. The manufacture and testing of duplicate specimens for each level of reinforcement in this second experiment was exactly the same as those used in the first experiment.

2.2. Fracture Toughness Testing of Laminated Wood Composites. The geometry of the specimens described above conforms to the requirement of the standard ASTM D5528-13 test for crack opening mode (mode I) interlaminar fracture toughness testing of unidirectional polymer composites [13]. The edges of specimens were covered with white correcting tape and marked with length scales (1 mm marks for the first 25 mm followed by 2 mm marks for a further 20 mm, and then 5 mm marks for an additional 20 mm, Figure 2). Opening forces were applied to specimens via hinges attached to the cross-head of a universal tensile testing machine (Instron® M3502) (Figures 2(a) and 2(b)). A cross-head speed of 1 mm/min was used, and crack length propagation was measured using a digital SLR camera (Canon® EOS 5D Mark II) with 24–105 mm zoom lens as shown in Figure 2(b). The camera captured an image as soon as the specimen opened. Subsequent images were captured every 20 seconds (until failure) using the tethering photo-capture software, Breeze® DSLR Remote Pro, on a PC. Each time-lapse image was saved in RAW format so the crack front position could be easily seen at high magnification within the software Adobe Photoshop® Raw processer (Figures 2(c) and 2(d)).

2.3. Fracture Toughness Calculation and Analysis of Data. Modified beam theory was used to calculate fracture toughness according to ASTM D5528-13 [13]. It should be noted that test results are primary "specimen properties" rather than "material properties" because calculated fracture toughness

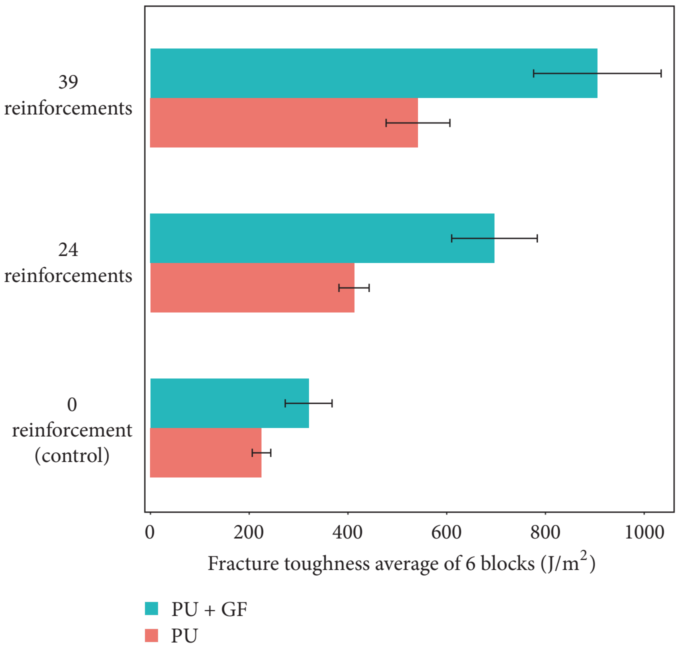


Figure 3: Fracture toughness values of specimens containing through-reinforcement and glass-fibre in adhesive bond lines versus fracture toughness of the controls.

values are dependent on the geometry of test specimens. The test results should therefore be regarded as "apparent fracture toughness" as suggested by fracture mechanics principles. Nevertheless, all the specimens (perforated and unperforated controls) consisted of wood veneers with the same grain pattern and similar geometry and they contained identical levels of adhesive. Therefore, the apparent fracture toughness values are comparable between specimens.

Fracture toughness results from the main experiment were subject to analysis of variance to determine the effects of the two experimental factors, through-reinforcement (39 reinforcements versus 24 reinforcements versus 0 reinforcement) and adhesive modification (PU adhesive versus glass-fibre reinforced PU adhesive) as well as the interaction of these two factors on fracture toughness. Statistical computation used GenStat (Release 17.1), and results were tested for statistical significance at the 5% level ($p < 0.05$). Results are presented in graphs plotted using the program R (version 3.2.3) and least significant difference bars derived from the ANOVA are included on each graph. These error bars can be used to determine if differences between individual means are statistically significant ($p < 0.05$).

2.4. Scanning Electron Microscopy of Fracture Surfaces. The microstructure of fractured surfaces in tested specimens containing 39 reinforcements was examined using scanning electron microscopy. Small wood specimens measuring 5 mm × 5 mm were carefully cut from the surface of fracture toughness specimens using a precision micro-table saw (Byrnes Model Machines Co.) equipped with a 10 cm diameter blade. Care was taken to ensure that fracture surfaces were not damaged during the preparation of specimens. Specimens were mounted on aluminium stubs using double-sided adhesive tape. They were then sputter coated with an 8 nm layer of gold and examined using a Zeiss UltraPlus analytical field emission scanning electron microscope (SEM) operating at 15 kV and a working distance of 13.1 to 14.0 mm. Selected secondary electron images were saved as TIFF files.

3. Results

3.1. Fracture Toughness Tests. The introduction of adhesive through-reinforcement in the birch wood composite significantly improved fracture toughness (Figure 3). The improvement of fracture toughness was significantly ($p < 0.05$) greater in samples containing higher levels of reinforcement (Figure 3). Fracture toughness was also significantly improved by reinforcing adhesive bond lines with glass-fibre (Figure 3). Analysis of variance indicated that there was no significant ($p > 0.05$) interaction of through-reinforcement and addition of glass-fibre to adhesive bond lines on fracture toughness. Nevertheless, the addition of glass-fibre to adhesive bond lines was more effective at improving the fracture toughness of the birch composite containing through-reinforcement than it was at improving the fracture toughness of the control. For example, the addition of glass-fibre to adhesive bond-lines improved the fracture toughness of the control by 42%, whereas comparable figures for composites containing through-reinforcement were 69 (24 reinforcements) or 67% (39 reinforcements).

The effects of through-reinforcement and addition of glass-fibre to adhesive bond lines on 5% maximum fracture toughness values of specimens, a reporting parameter for ASTM D5528-13, are shown in Figures 4 and 5, respectively. These figures also show other critical fracture characteristics of tested specimens, and demonstrates the effectiveness of

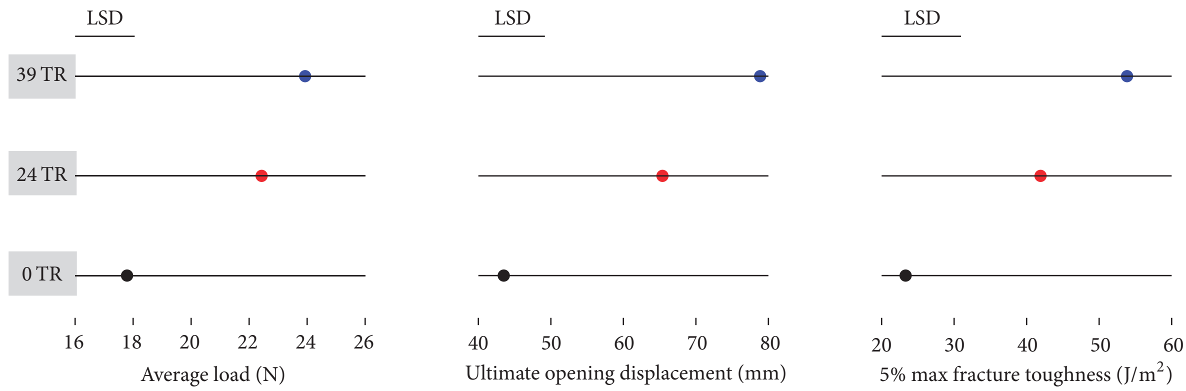


FIGURE 4: Effects of through-reinforcement (TR) (39 through-reinforcements versus 24 through-reinforcements versus 0 through-reinforcement) on some critical fracture characteristics of laminated birch wood specimens.

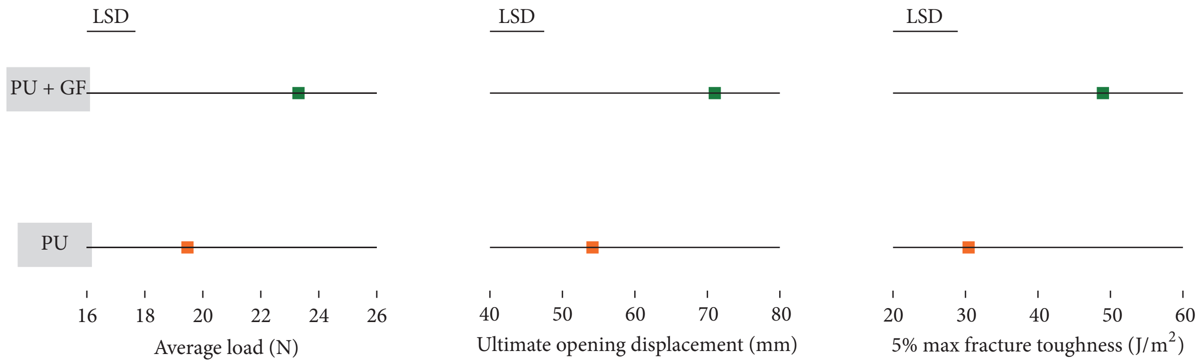
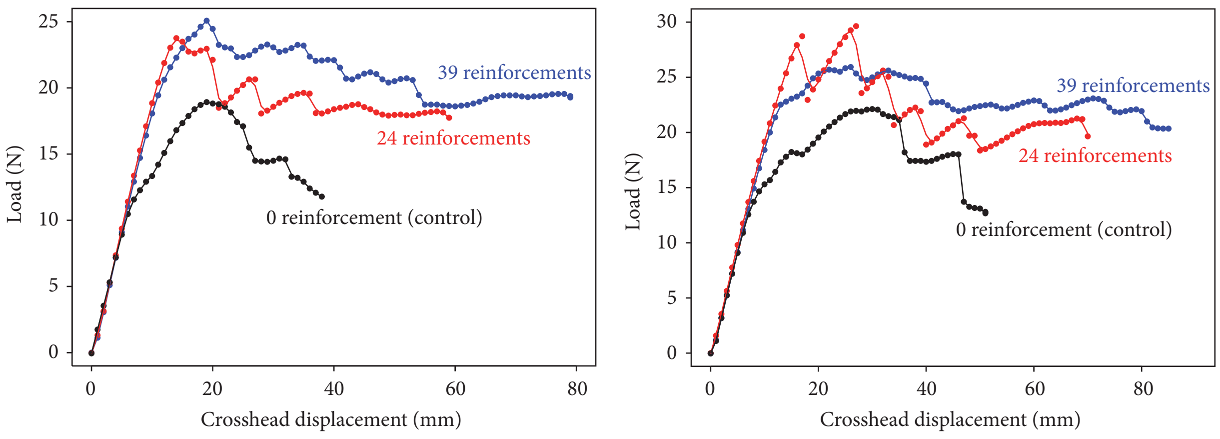


FIGURE 5: Effects of reinforcement of polyurethane adhesive (PU) with glass-fibre (GF) on some critical fracture characteristics of the laminated birch wood specimens.



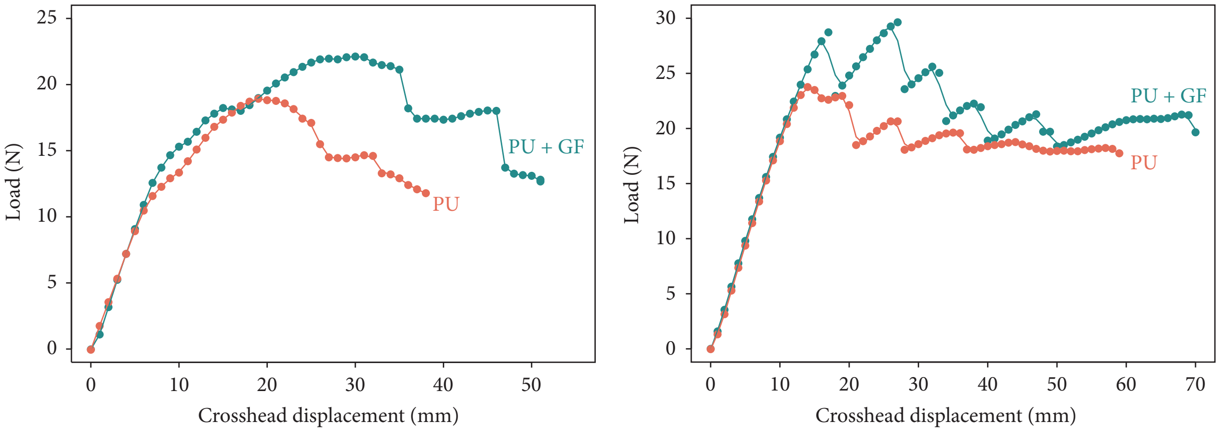
(a)

(b)

FIGURE 6: Load-displacement curves of specimens with different levels of through-reinforcement and bonded using unmodified polyurethane (PU) adhesive (a) or a glass-fibre reinforced PU (b).

through-reinforcement, and also adhesive bond-line reinforcement on the fracture toughness of the birch wood composite.

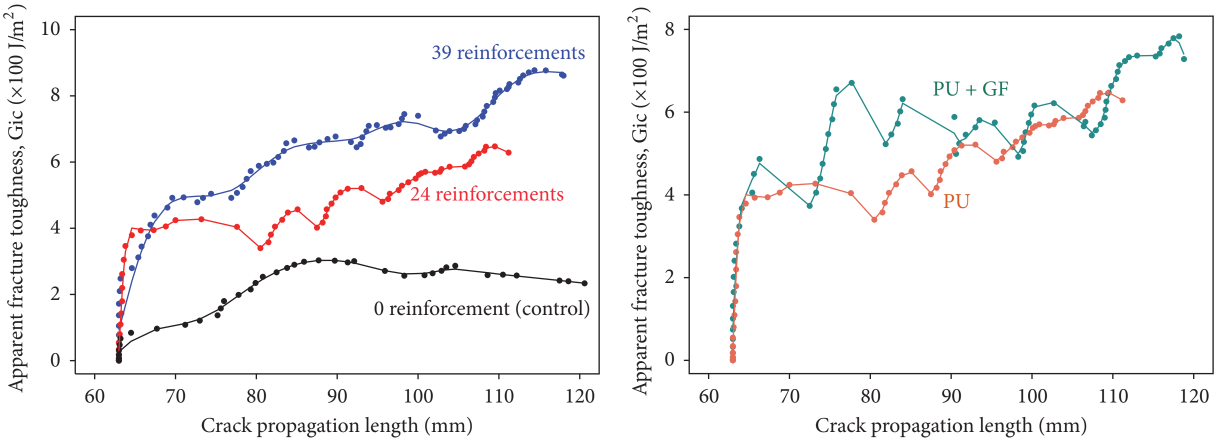
Through-reinforcement of the birch composite appeared to arrest propagation of the crack induced during fracture toughness testing. This effect is suggested by load-displacement curves of specimens during testing (Figure 6), which show that load increased abruptly and then increased more slowly. During the latter phase there were increases in load as the crack encountered through-reinforcement. Load increases are sinusoidal in specimens with through-reinforcement at the lower level, but higher levels of reinforcement appear to smooth the sinusoidal variation of load. The load carrying capability (y-axis) of the specimens with



(a)

(b)

Figure 7: Load-displacement curves of specimens with unmodified polyurethane (PU) adhesive or adhesive modified by the addition of 5.5% w/w glass fibre (GF): (a) No through-reinforcement; (b) through-reinforcement (24 reinforcements).



(a)

(b)

Figure 8: Mode I crack growth resistance curves (R-curves) of (a) polyurethane (PU) adhesive with different levels of through-reinforcement; and (b) different adhesive types (PU or PU + GF) with the same level of through-reinforcement (24).

through-reinforcement was generally higher than that of the control. Furthermore, specimens with through-reinforcement withstood greater mode I opening displacement (x-axis) until ultimate failure than the control (Figure 6).

Results in Figure 6 show the positive effects of through-reinforcement on load sustained by specimens bonded with an unmodified polyurethane adhesive (Figure 6(a)), and specimens bonded with a polyurethane adhesive reinforced with 5.5% glass-fibre (Figure 6(b)). The effect of adding glass-fibre to adhesive bond lines on load sustained by specimens can be clearly seen in Figure 7. This figure shows that adding glass-fibre to the PU adhesive increased the load carrying capacity of specimens and extended the maximum mode I opening displacement of specimens (Figure 7).

Crack resistance curves of specimens, also known as R-curves, accord with load displacement results and indicate the positive effects of through-reinforcement and adhesive modification on fracture toughness (Figure 8). They also support the suggestion that increases in toughness of specimens with through-reinforcement resulted from the ability of the reinforcement to arrest crack propagation.

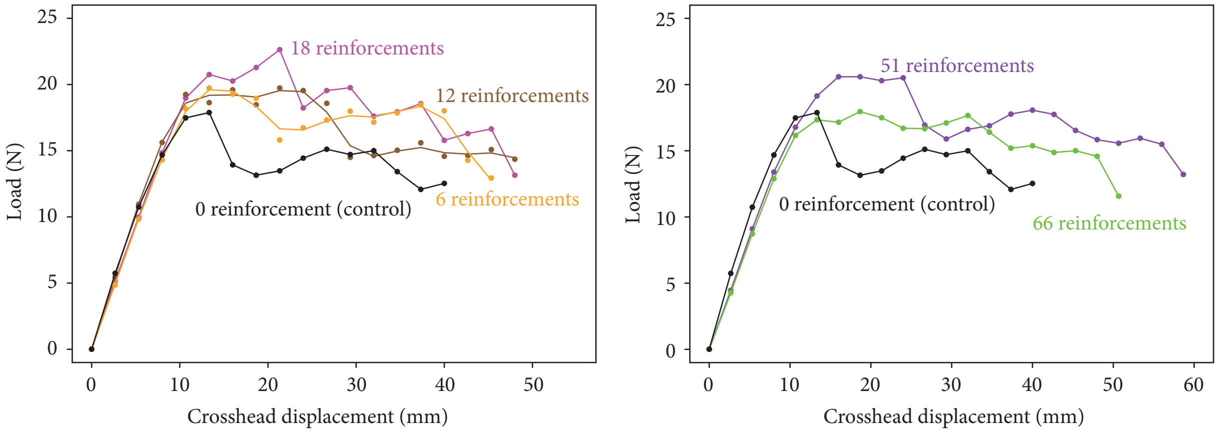
Results in Figure 9 show the effects of different levels of adhesive through-reinforcement (0, 6, 12, 18, 51, and 66 reinforcements) on the load sustained by specimens bonded with unmodified PU adhesive. Table 1 shows the effects of different levels of adhesive through-reinforcement on the fracture toughness and mode I opening displacement of specimens. The results in Figure 9 and Table 1 confirm that through-reinforcement improves fracture toughness and indicate that improvements in fracture toughness depend on the level of reinforcement. The optimal level of reinforcement appeared to be 39 reinforcements per veneer strip (2.33 per cm^2).

3.2. Scanning Electron Microscopy of Fracture Surfaces.

Scanning electron photomicrographs of fracture surfaces in laminated birch wood specimens after mechanical testing suggest how through-reinforcement and addition of glass-fibre to

Table 1: Effects of different levels of adhesive through-reinforcement on the fracture toughness and mode I opening displacement of laminated birch wood specimens bonded with an unmodified polyurethane adhesive.

No. of reinforcements	Density of reinforcements (N/cm^2)	Fracture toughness (J/m^2)	Displacement (mm)
0 (control)	0	225	41
6	0.36	287	40
12	0.72	287	47
18	1.08	327	48
24	1.43	412	56
39	2.33	542	66
51	3.04	340	57
66	3.94	353	52



(a) (b)

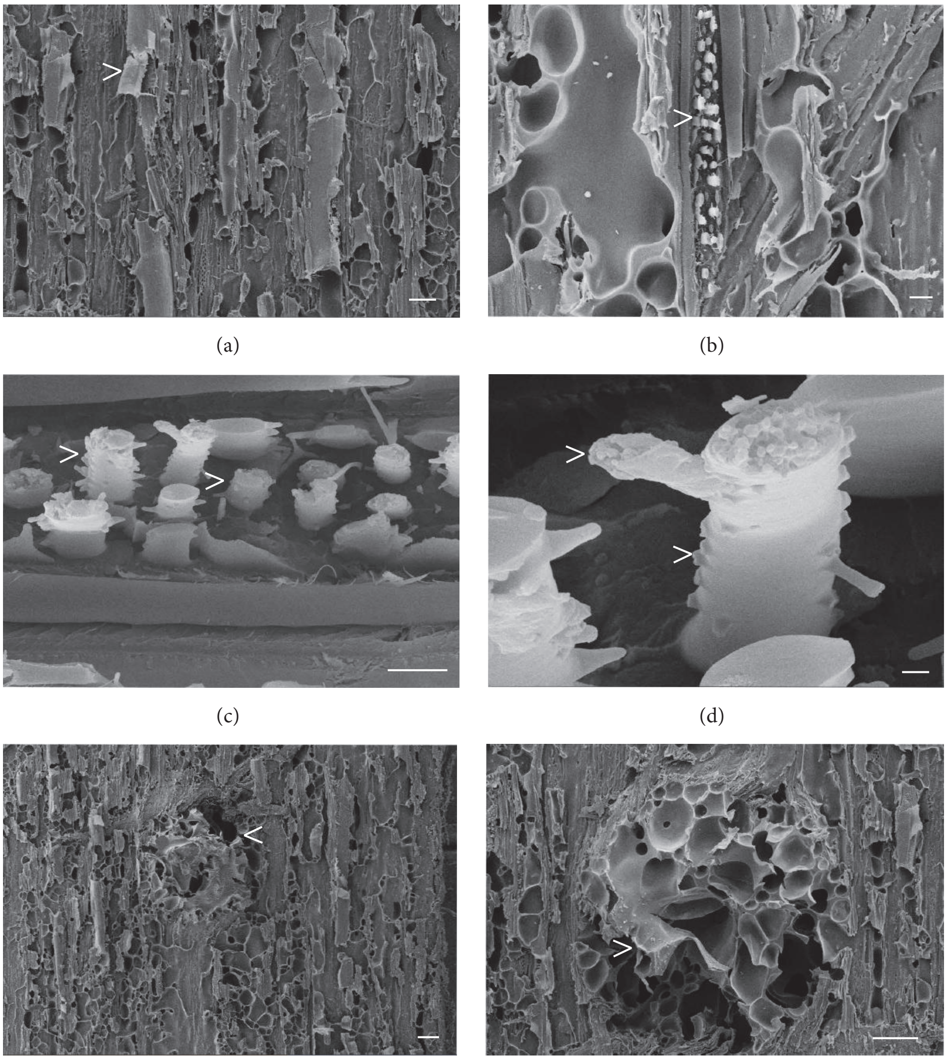
Figure 9: Load-displacement curves during double cantilever beam (DCB) mode I fracture toughness tests of specimens with 6 different levels of through-reinforcement (including the control): (a) reinforcement levels less than 24 (<1.43/cm^2); (b) reinforcement levels greater than 39 (>2.33/cm^2).

adhesive bond lines increased fracture toughness. They also cast some light on the bonding mechanism of polyurethane adhesives used with wood.

Polyurethane adhesive was clearly visible at the fracture surfaces of birch composites bonded with unmodified adhesive (Figure 10(a)). Residual adhesive at fracture surfaces exhibited tearing and pull-out, which may have contributed to adhesive bond strength (arrowed top left in Figure 10(a)). In addition, we observed pull-out of adhesive that had penetrated the cells in the rays of birch (arrowed in Figures 10(b) and 10(c)). The pillar-shaped structures that projected from the cells within rays had branches, some of which appeared to have fractured during testing (arrowed in Figure 10(d)). We also observed fracture, pull-out, and lateral displacement of adhesive columns that provided multiple through-reinforcement of the birch composite (arrowed in Figures 10(e) and 10(f)). The same patterns of failure were noted at fracture surfaces of composites bonded with polyurethane adhesive containing glass-fibre (Figures 11(a)–11(c)). In addition, we observed pull-out of fibre-bundles at fracture surfaces (arrowed in Figure 11(d)). Glass-fibre was clearly evident at fracture surfaces and there was evidence of pull-out of the glass-fibres in horizontal glue-lines (arrowed left in Figure 11(a)) and also within the adhesive columns that provided through-reinforcement (arrowed in Figures 11(e) and 11(f)).

4. Discussion

Our results support our hypothesis that introduction of through-reinforcement across veneers increases the fracture toughness of a laminated birch wood composite and show that improvements in fracture toughness depend on the level of reinforcement. Our results also show that glass-fibre reinforcement of adhesive bond lines significantly increases fracture toughness. They also suggest how the two different types of reinforcement increased fracture toughness. The addition of glass-fibre to adhesive bond lines appeared to provide reinforcement during crack propagation, hence consuming fracture energy. This suggestion accords with the results of many studies that have examined the use of glass-fibre to reinforce and improve the toughness of other composite materials, for example, vinyl-ester polymer composites [15], polypropylene composites [16], and dental particulate composites [17]. There have been no previous studies to our knowledge of the use of adhesive through-reinforcement to increase the fracture toughness of laminated wood composites. Therefore, we cannot compare our findings



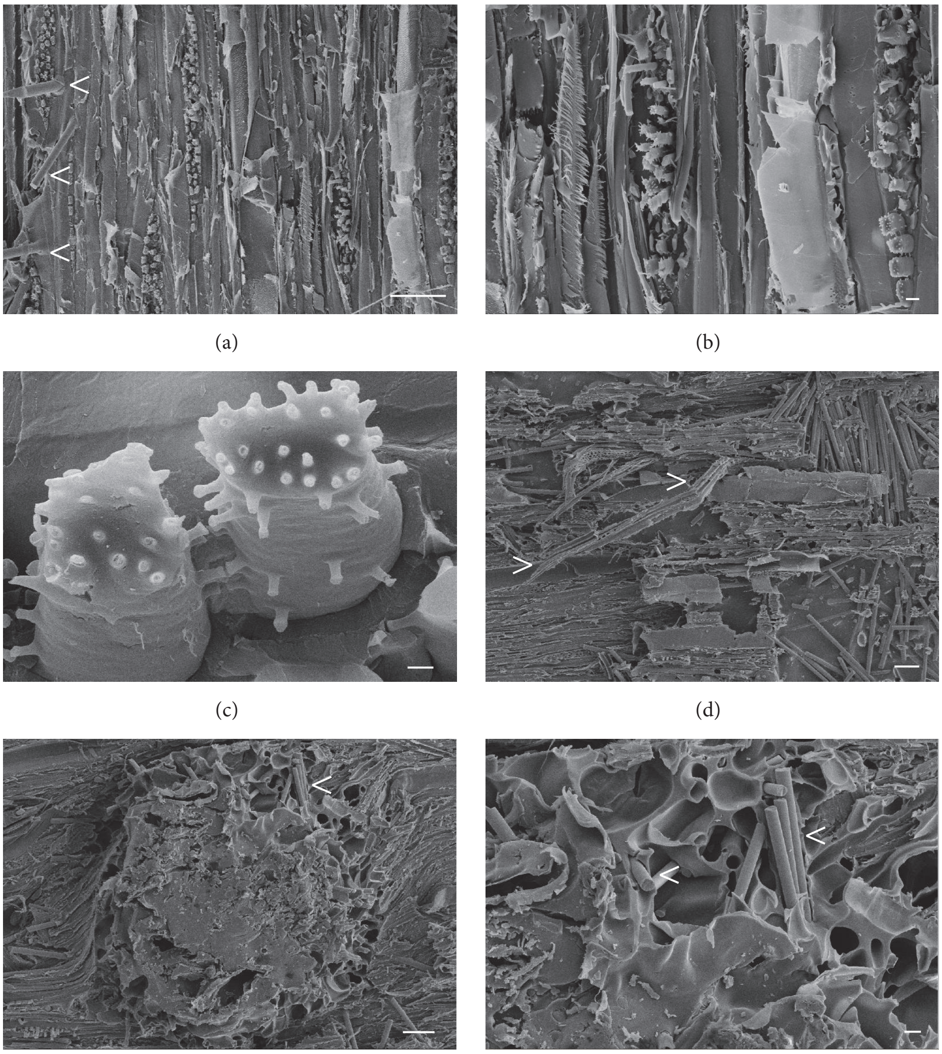
(a) (b)

(c) (d)

(e) (f)

Figure 10: Fracture surfaces of a laminated birch wood composite bonded with unmodified single component polyurethane adhesive; (a) adhesive on fractured wood surface showing pull-out and microfracture of adhesive that partially covers the wood surface (arrowed left; scale bar = 100 μm); (b) fractured wood surface showing a multiseriate ray (centre) and pull-out of adhesive from the lumens of individual ray cells (arrowed centre; scale bar = 20 μm); (c, d) higher magnification photographs showing the pillars of adhesive that pulled out of ray cells shown in (b). Note the fractured ends of the pillars and the intact and fractured side-arms (branches) (arrowed left and centre; scale bars = 10 μm (c) and 1 μm (d)); (e) fractured column of adhesive that provided through-reinforcement to the composite (arrowed centre) and residual adhesive on the fractured wood surface (scale bar = 200 μm); (f) higher magnification photograph of the adhesive column shown in (e). Note the fracture and distortion of the adhesive column and the distortion of the adjacent wood (arrowed; scale bar = 200 μm).

with those of previous researchers. However, the multiple through-reinforcement provided by adhesive columns running radially in specimens has some similarities with that provided by rays (radial ribbons of woody tissue), which are aligned in the same direction as the adhesive columns engineered here. Our SEM images of fracture surfaces suggested that rays provided reinforcement, and Reiterer et al. [18] in their study of the fracture toughness of three hardwoods and the softwood, spruce, suggested that "the rays (in solid wood) can be considered as reinforcements in the radial directions." Furthermore, their load displacement graphs obtained during fracture testing of hardwoods have some similarities to those obtained here [18]. Hence, we suggest that adhesive through-reinforcement provided reinforcement behind the crack tip, hindering crack propagation and absorbing fracture energy. This suggestion is supported by the wave-shape of the crack propagation resistance curves (R-curves) of specimens containing adhesive through-reinforcement. The "wave peaks" indicate abrupt increases in fracture energy when the crack propagated through adhesive columns. This bridging effect occurred at the macroscale, but it complements that provided by adhesive bond reinforcement with glass-fibre. Such a complementary effect was more pronounced in specimens with through-reinforcement than in the controls, possibly because the glass-fibre reinforced the adhesive columns in the birch wood composite, in addition



(a) (b)

(c) (d)

(e) (f)

Figure 11: Fracture surfaces of a laminated birch wood composite bonded with a single component polyurethane adhesive containing 5.5% w/w milled (60 mesh) glass-fibre: (a) fractured wood surface showing pull-out and fracture of glass-fibre (arrowed left) and wood cells; pull-out of adhesive from ray cells; and adhesive that partially covers the wood surface (scale bar = 100 μm); (b-c) higher magnification photographs [from (a)] showing fracture of wood cells and pull-out of adhesive from the lumens of individual ray cells (scale bars are 10 μm (b) and 1 μm (c)); (d) fractured wood surface showing residual adhesive, pull-out of bundles of fibres (arrowed left and centre) and presence of numerous glass-fibre strands (right) (scale bar = 100 μm); (e-f) fractured column of adhesive containing embedded glass-fibre that provided through-reinforcement to the composite (arrowed top right of centre in (e), and centre and right in (f)). Note the fracture and distortion of the adhesive column and the distortion of the adjacent wood (scale bars are 100 μm (e) and 20 μm (f)).

to their ability to reinforce adhesive bond lines aligned in the x-y direction.

Birch plywood is a preferred material used for the construction of wooden aircraft, as mentioned above, and fracture toughness is an important property of composites used for this application. Nevertheless, as pointed out by Reiterer et al. [18] there are few studies of the fracture toughness properties of hardwoods such as birch. The fracture toughness properties of composites depend on good adhesion between adhesive and the matrix [19]. Adhesive bonding of wood involves a mix of physicochemical interactions including mechanical interlocking provided by penetration of adhesive into the porous microstructure of wood [20]. Penetration of adhesives into hardwoods occurs easily via the open pores (vessels) that are readily apparent in species such as oak. Hence, reviews of wood adhesion have focused on such an effect [20, 21]. The penetration of adhesives into rays was mentioned by Vick [20] as possibly having a detrimental effect on adhesion because “radially oriented rays can allow excessive flow and overpenetration” (of adhesive). Our SEM photomicrographs showed pull-out of adhesive from cells in rays suggesting that penetration of adhesive into the rays located at the tangential surface of rotary peeled birch veneer improved adhesion. The pillars of adhesive that pulled out from ray cells had side arms possibly produced by penetration of adhesive from ray cell lumens through pits (openings) into the lumens of adjacent cells. Some of these side arms were fractured, possibly indicating that they contributed to the fracture toughness of the composite. This observation suggests that penetration of adhesive into rays can have a positive effect on adhesion and underscores the need for further studies of the effects of wood microstructure on the adhesive properties and fracture toughness of composites made from hardwoods.

The fracture toughness of the model composite we tested was clearly improved by adhesive through-reinforcement and also the addition of glass-fibre to adhesive bond lines. Glass-fibre has been added to polymer composites to improve their mechanical properties, as mentioned above [16], and a study by Dorey and Cheng [22] showed that the mechanical properties of laminated spruce-pine-fir beams were significantly improved by reinforcing the phenol-resorcinol glue lines of the beams with pultruded glass-fibre straps. They concluded that "the application of glass-fibre reinforcing has a potential to play a significant role in glulam structures" [22]. Hence, the addition of glass-fibre to adhesives could be a practical means of improving the fracture toughness of veneer-based wood composites used in demanding applications. Clearly, our means of creating through-reinforcement, which also significantly improved the fracture toughness of our model composite, would be more difficult to implement in practice than adding glass-fibre to adhesive bond lines. However, the approach is attractive because significant increases in fracture toughness were achieved without increasing the level of adhesive in the composite. Therefore, it would be worthwhile to explore approaches that are more practical than precision drilling as a means of perforating veneer. One possible approach could involve passing veneer through a roller containing slitting knives, as has been done in the past to "reduce the tendency of rotary peeled veneer to distort when it is used to manufacture plywood" [23]. Further research would be needed to determine whether slit-like perforations and any resulting through-reinforcement would be as effective as the cylindrical connections used here to improve fracture toughness of composites made from birch wood veneer. An alternative related approach to improving fracture toughness would be to nail the composite in the Z-direction using thermoplastic polymer nails. Laminated wood composites that are bonded together with nails are available commercially [24], and such an approach might work with other types of wood composites. In support of this suggestion, the automated insertion of thin metal wires through laminates (Z-pinning) is highly effective at improving the fracture toughness of laminated synthetic composites and is used commercially to improve the properties of aerospace and automotive composites [3]. The Z-pins used in these applications are made from materials such as titanium alloy that are strong and stiff. This desirable property of Z-pins suggests that adhesives that are stronger than the polyurethane adhesive tested here might be better at increasing fracture toughness of laminated wood composites via adhesive through-reinforcement. Further research would be needed to test this hypothesis. We have demonstrated in recently published work that adhesive through-reinforcement has a positive effect at reducing the moisture-induced swelling of laminated wood composites [14], in addition to its beneficial effects on fracture toughness. Further research is needed to examine the effect of adhesive through-reinforcement on the elastic modulus, modulus of rupture, and internal bond strength of laminated wood composites. Significant improvements to the properties of such composites and also others derived from renewable materials, for example, bamboo, could allow them to compete more effectively in some applications with synthetic composites, with resulting benefits in terms of sustainability and the environment [25].

5. Conclusions

We hypothesised that introduction of through-reinforcement across veneers, and glass-fibre reinforcement of adhesive bond lines would significantly increase the fracture toughness of a laminated birch wood composite. Our results support this hypothesis, and we have shown that improvements in fracture toughness are related to the level of through-reinforcement. We have suggested how through-reinforcement and glass-fibre reinforcement of adhesive bond lines increase the fracture toughness of the composite. We have also suggested how the ability of through-reinforcement to increase fracture toughness could be improved further. Through-reinforcement is potentially an attractive, cost-effective, approach to improving fracture toughness, because increases in this property were achieved without the use of additives or increasing the level of adhesive in the composite. However, further research is needed to develop practical ways of creating perforations that facilitate adhesive through-reinforcement of laminated wood composites.

Competing Interests

The authors declare that they have no competing interests.

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