Fracture Behaviour of Tropical Hardwood Under Tensile Load

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This paper reports on the fracture behavior of a hard wood known as Selanga Batu (*Shorea* spp) with different structure under tensile stress at various strain rates (10-100mm/min). It was found that the structure had significant effect on the modulus of elasticity and yield strength of the wood. Wood with high percentage of ray parenchyma exhibited lower modulus of elasticity and yield strength. Ray parenchyma in wood acted as the weakest plane for crack to propagate in a step-wise manner. However, large variation found in test results make it not possible to evaluate whether the strain rate affects the ultimate strength and the fracture strain. Since the values of the modulus of elasticity obtained at a given strain rate had very small variation, the effect of strain rate on the modulus of elasticity and yield strength could be examined. It was found that the strain rate did not affect the modulus of elasticity and the yield strength of the wood.

Keyword: Failure, crack, microstructure, mechanical properties

I. INTRODUCTION

Dill-Langer et al. [1] reported that soft wood failed in a brittle manner when subjected to tensile stress parallel to the fiber. The relationship between the applied force and displacement was nearly linear to failure, and failure was sudden and catastrophic. The experiment results showed that the rupture and the strength of wood was governed by the flaws distributed along the fibers and the tensile strength decreased with an increase in the size of the wood specimen. In the tensile test carried out on a soft wood, Galicki and Czech [2] found that the density of the wood had significant influence on the tensile strength of wood i.e. the tensile strength increased with an increase in the density of the wood. When tensile stress was applied along the grain, the wood ruptured either transversely to the grain or along the grain. Other workers [3] had reported splinter fracture due to the high degree of anisotropy of the wood in the tension test carried out parallel to the grain. The tensile strength and elastic modulus along the grain could be in the range of 10-20 times higher than those of measured across the grain [3],[4].
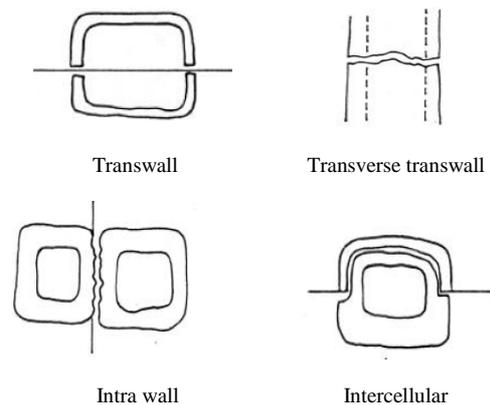
Fig. 1 Types of fracture of cells [8]

Several workers have carried out in situ tensile tests on various wood samples to continuously monitor the crack initiation and propagation, and fracture mechanism [5]. There are three types of fracture: transwall, intrawall, and intercellular (Fig 1). Transwall failure is a result crack propagation across the wall. Intrawall failure is due to cracking within the cell wall and around the lumen.

Intercellular failure occurs at the middle lamella and represents the separation of wall. When comparing the fractured surfaces of green and dried specimens fractured in tension, Kifetew et al. [6] found that in the latter case, transwall failure occurred and fracture of green specimens had been dominated by intrawall failure. Transwall failures normally occurred on thin-walled cells, such as the early wood tracheids in softwoods and vessel, and parenchyma cells in hardwoods. Fracture in low density wood tends to be transwall, while for higher density wood both transwall and intercellular fracture are likely to take place [7].

II. MATERIALS AND METHODS

Fracture behavior of Selanga Batu (*Shorea* spp) under tensile stress was carried out on an Instron Universal Testing Machine at the rates of 10, 20, 50, 70 and 100 mm/min. Selangan Batu which has been widely grown in tropical countries is characterized as hard wood. The gage length of the wood specimen was 180 mm. The length and width of the specimens were 280 mm and 25 mm, respectively, as illustrated in Fig 2. The wood specimens had either 0^0 and 45^0 ring orientations as shown in Fig 3. All wood specimens had a similar age as they were taken from the same ring of the tree. The load versus displacement was recorded continuously during the test. From the load-displacement graph, the stress-strain graph was plotted and thus the mechanical properties of the wood were determined.
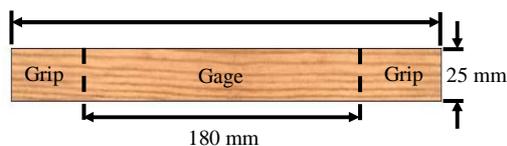
Fig. 2 Dimension of the test specimen.
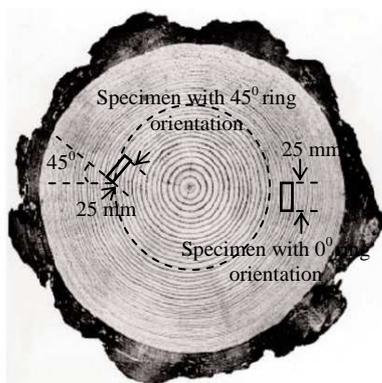
Fig 3. Wood specimens with 0^0 and 45^0 ring orientations were obtained from the same ring of the tree.

Density and moisture content in wood had significant influence on the modulus of elasticity, yield strength, and ultimate strength of woods[2],[9].The strength of the wood was found to decrease with an increase in the moisture content [9]. All the tests specimens used in this study had been baked to 12 ± 1 % moisture content. The density also varies between trees of the same species and between different parts of the same tree as they have different structure. The density of the wood specimens with 0^0 and 45^0 ring orientations after being baked was found to be 0.8976 ± 0.013 and 0.8972 ± 0.010, respectively.

III. FAILURE MODE

10mm/min 30mm/min 50mm/min 70mm/min

(a)

10mm/min 30mm/min 50mm/min 70mm/min

(b)
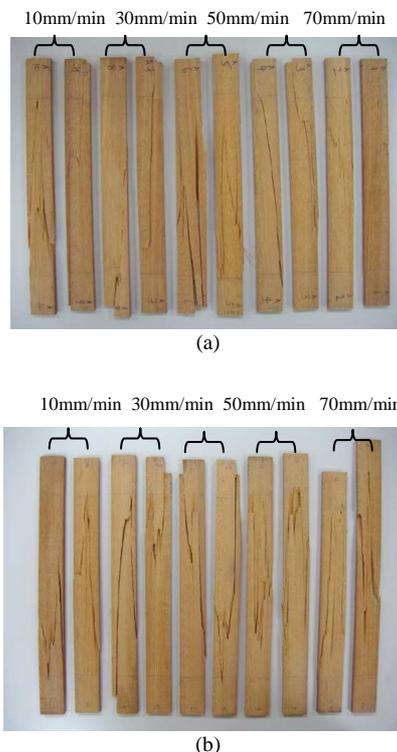
Fig. 4 Specimens with ring orientation of (a) 0^0 and (b) 45^0 after tensile test.

The specimens with different ring orientations tested at various strain rates are shown in Fig 4. Generally, there are two modes of failure: shear and splinter as shown in Fig 5. The specimens failed in shear mode has been due to crack propagating in a direction about 45^0 to the applied stress. The crack propagation of in splinter mode is complex. The initial crack may start anywhere in the gage transversely as primary crack before propagating in zigzag direction as shown in Fig 5(b). Initial crack is difficult to locate and identify after an audible initial "burst" sound of the breaking of fiber. It has been found that specimens with the ring orientation of 0^0 failed in shear mode. Whereas, specimens with the ring orientation of 45^0 failed in splinter mode. No change in the failure mode with strain rate has been observed.

(a)

(b)
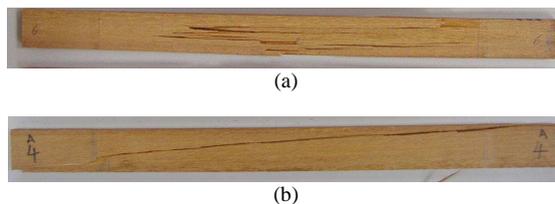
Fig. 5 (a) Shear and (b) splinter failure are the two common failure patterns observed on the tested specimens.
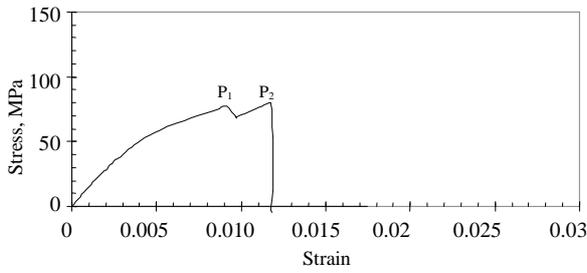
Fig. 6 Stress-strain curve obtained in the test conducted at 10 mm/min using wood with ring orientation of 45°.

If the test specimen fractured completely after the crack had propagated, a rapid drop in the load would be observed and a burst sound would be heard. In some circumstances, two "burst" sounds were heard. The stress caused the first "burst" sound is P_1 as indicated in Fig 6. Upon reaching P_1, a sudden drop followed by an increase in the stress was observed. After reaching the second peak value of P_2, the stress dropped to 0 as the specimen had completely lost its load-bearing capacity. In many tests, the value of P_2 was found to be higher than the P_1. This indicates that the specimen still had high load-bearing capacity after the first rupture. On the conservative side, the first peak value i.e. P_1 was taken as the ultimate strength of the wood.

IV. MECHANICAL PROPERTIES FROM STRESS-STRAIN GRAPH

The modulus of elasticity and yield strength for the woods with different ring orientations determined from the tensile tests are shown in Table 1. The modulus of the wood is the initial linear slope part of the stress-strain graph. The yield strength is the stress value of the intersection point between the straight line parallel to the slope of the stress-strain graph at 0.2% strain and the stress-strain curve.

The wood specimens with the same ring orientation tested at a given speed fractured at the strain of between 0.10 and 0.35. Tests carried out on the wood specimens with the same ring orientation at a given speed gave ultimate strength values of between 70-145 N/mm^2. Fig 7 shows that the tests, conducted at the same strain rate using specimens with the same fiber orientation, give very different values of ultimate strength and fracture strain. Due to a significant variation in the test results, it is not possible to evaluate whether the strain rate affects the ultimate strength and the fracture strain. Since the values of the modulus of elasticity obtained at a given strain rate has very small variation of 2%, the effect of strain rate and fiber orientation on the modulus of elasticity can be examined. However, it has been found that the strain rate did not affect the modulus of elasticity and the yield strength of the wood. The wood with 90^0 ring orientation has higher modulus of elasticity and yield strength than the wood with 45^0 ring orientation. This indicates that the wood with 45^0 fiber orientation has weaker structure.

TABLE I
MECHANICAL PROPERTIES OF THE WOOD WITH (a) 0^0 AND (b) 45^0 RING ORIENTATION OBTAINED FROM THE TENSILE TESTS USING DIFFERENT STRAIN RATE. WOOD WITH 90^0 RING ORIENTATION HAD HIGHER MODULUS OF ELASTICITY AND YIELD STRENGTH THAN THE WOOD WITH 45^0 RING ORIENTATION. STRAIN RATE DID NOT AFFECT THE MODULUS OF ELASTICITY AND THE YIELD STRENGTH.

Strain rate (mm/min)	Modulus of elasticity (N/mm^2)	Yield strength (MPa)
10	14392	69.00
30	14946	71.00
50	15485	72.00
70	14800	69.50
100	14893	70.00

(a)

Strain rate (mm/min)	Modulus of elasticity (N/mm^2)	Yield strength (MPa)
10	16505	82.50
30	16245	81.25
50	16422	78.00
70	16562	79.50
100	16410	82.00

(b)
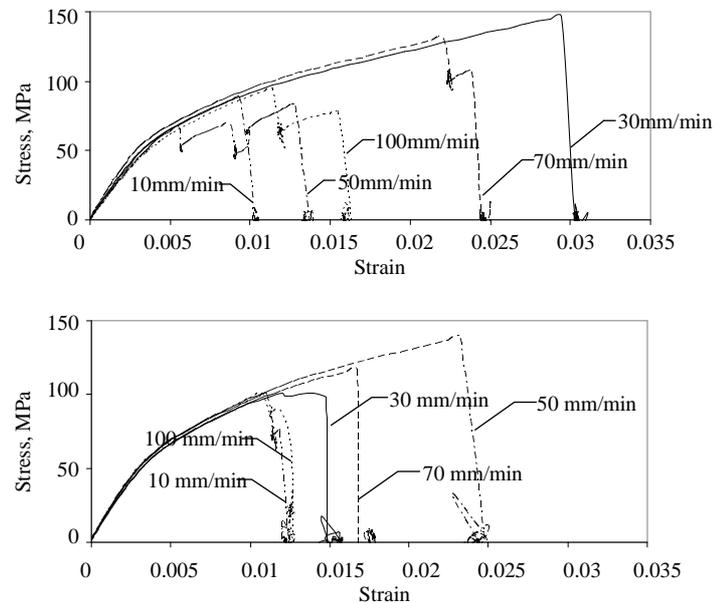
Fig. 7 Stress-strain curves obtained for woods with ring orientation of 0^0 at various strain rates. For a given strain rate, the ultimate strength and fracture strength varied between 100-145 MPa and 0.01-0.035, respectively.

V. MICROSCOPIC INVESTIGATION

Scanning electron microscope (SEM) is used to investigate the failure in the microstructure cells including the type of failures. Specimens with 0^0 and 45^0 ring orientations showed evidence of intercellular (IC), intrawall (IW) and transwall (TW) failures. Specimens with 0^0 and 45^0 had different structure which resulted in different crack propagation mechanisms. Specimens with 45^0 ring orientation has more ray parenchyma (refer to Fig 8) that serves as failure points. The cell wall of the rays is thin compared to the fiber. It is likely that crack is initiated at the ray parenchyma as it is the main spot of mechanical weakness in bulk wood subjected to tension perpendicular to the grain [10].

Fig. 8 Microstructure of wood specimens with different orientations [8].

Failure mechanism for specimen with 45^0 ring orientation can be explained as the schematic in Fig 9. When tensile load is applied to the rectangular cross section specimen, radial ray parenchyma is subjected to high stress concentration, which will eventually lead to the initial crack at the bonding between rays and fibre and rays to rays. Two crack propagation mechanisms are possible i.e. crack propagation in *A* manner due to weak bonding between rays and crack propagation in *B* manner due to the thin cell wall of the rays parenchyma. The fracture mechanism can proceed in a step-wise manner from the first plane of normal ray *A* to the second plane of ray *B* [11]. This explains why cracks formed in wood with 450 ring orientation propagate in a zigzag manner, resulting in step-like fractured surface as shown in Fig 10.
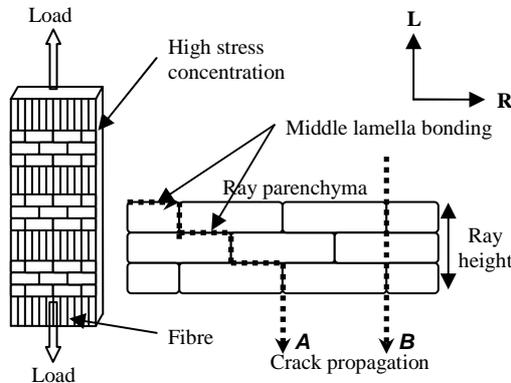
Fig. 9 Crack propagation in wood with 45^0 ring orientation.
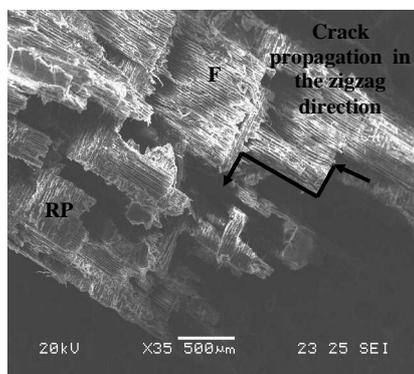
Fig. 10 Fracture surface produced by crack propagation in the zigzag direction. F: fibre, RP: rays parenchyma.

VI. CONCLUSION

Fracture behavior of a hard wood known as Selanga Batu (*Shorea* spp) with different structure under tensile stress at various strain rates (10-100mm/min) was investigated. It was found that the structure had significant effect on the modulus of elasticity, the yield strength of the wood and the crack propagation. Wood with high percentage of ray parenchyma exhibited lower modulus of elasticity and yield strength. It was also found that the strain rate did not affect the modulus of elasticity and the yield strength of the wood. Due to large variation in the ultimate strength and fracture strain, it has not been possible to evaluate whether the strain rate affects the ultimate strength and the fracture strain.

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