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The fracture of wood under torsional loading

Zheng Chen · Brian Gabbitas · David Hunt

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Abstract A series of experiments have been carried out on hardwood (red lauan) and softwood (sitka spruce) test pieces using static and cyclic torsional loading under displacement control. Measurements of the applied torque, the corresponding angle of twist and the number of cycles to failure were recorded. It was found that under static torsional loading, the strength of both hardwood and softwood reduced as the grain orientation of the sample to the axis of twist increased from 0° to 90° with a corresponding decrease of elastic modulus. Hardwood is stronger than softwood. In the fatigue test, when the torsional load is plotted against cycle number, the results showed that under displacement control stress relaxation occurs. The *S–N* curve for softwood has a shallower gradient than that of hardwood, indicating that the torsional strength of softwood is less affected by fatigue loading than hardwood. In both static and cyclic torsional loading tests, the failure mode of hardwood is slow and incomplete, whereas, softwood fails suddenly and completely. The crack growth is along the tangential direction in the hardwood cross-section and in the radial direction in the cross-section.

Z. Chen (✉)
University of Toronto, Toronto, ON, Canada
e-mail: cxc620@yahoo.ca

B. Gabbitas
University of Waikato, Hamilton, New Zealand

D. Hunt
London South Bank University, London, UK

Introduction

There is much published literature on the fatigue of wood and wood materials [1–3]. Most research on the fatigue of wood materials in recent decades has been focussed on wood laminates, and for applications such as wind turbine blades, because wood has several advantages over other materials for blade construction materials [1, 4].

A literature review indicates that most investigations carried out for wood under torsional loading appear to be concerned with issues such as the effects of moisture content on fatigue behaviour [5] or temperature distributions during cyclic loading and their effect on fatigue life [6–8]. There is little published data presenting the effect of grain angle on both the static torsional shear strength and the shear stress versus cycles to failure for torsional loading. From an engineering perspective this is not surprising since torsional loading is not perceived to be of general importance. However, in some applications where flexure is dominant, there may also be some twisting. For example, the blades in a wind turbine would be subjected to torsional as well as flexural loading.

In order to fill some of the gaps in current knowledge, this research was initiated to carefully investigate the influence of grain orientation on the behaviour of softwood and hardwood under torsional load and displacement controlled fatigue with particular attention being given to the mechanisms of crack nucleation and growth.

Torsional fatigue experiments

Test pieces

The hardwood, Red Lauan and the softwood, Sitka Spruce, each with different grain orientations were selected for this investigation. The test pieces were solid cylinders 220 mm long with a 20 mm diameter cross-section with square expanded ends. Angle of twist measurements were taken over a 120 mm length using a calibrated strain gauge transducer.

Torsion experiments

In this work a Mayes Servohydraulic tensile testing machine (ESH 100 kN model) with a 2.5 kN MTLC 400 load cell was used for carrying out torsion fatigue tests.

In order to convert the linear movement of the Mayes servohydraulic testing machine to a rotational movement, and clamp the wood sample effectively, a special attachment rig was designed. The rig consisted of two arms, two bearing bases, two sample grips, two square plates and one bedplate which was attached to the tensile test machine during testing. The bedplate was fixed to two square plates which could be clamped to the columns of the tensile testing machine. The arms were connected to the bearing bases by moving shafts with four rolling bearings for each arm, to facilitate smooth movement of the arm. Each sample grip was square and made of two parts. One part was fixed to the arm using bolts and the other connected to the former part using two bolts so that it formed a closed groove for clamping the sample without crushing it. The closed groove was also square but its line of symmetry made a 45° angle with the grip's line of symmetry. The end of one arm was connected to the moving ram of the machine to exert torsional loading on one end of the specimen through the sample's grips. The end of the other arm was connected to the load cell of the machine (Fig. 1). Both arms were perpendicular to the load axes before the testing began in order to apply the load along the tangential direction of the sample (Fig. 2).

In the static torsional test, the load speeds were set at 3–4° twist angle per second. In the torsional fatigue tests, the rate of load cycling was always less than 10 cycles per minute (0.17 Hz) under unidirectional (pulsating) load.

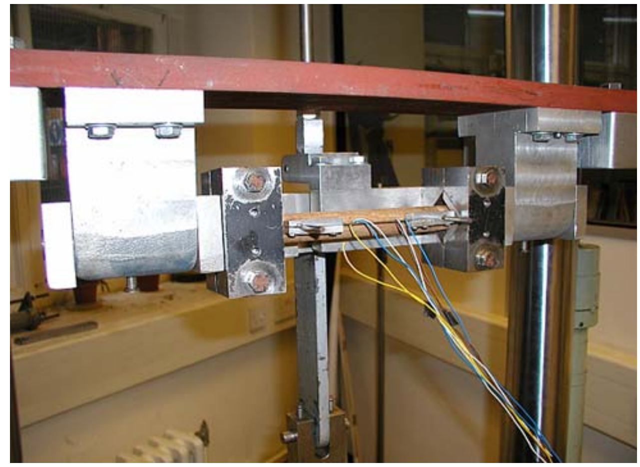

Fig. 1 Details of the torsional loading attachment for a Mayes tensile testing machine

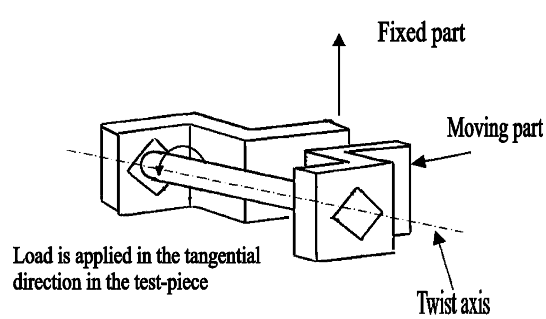

Fig. 2 Schematic diagram to illustrate tangential loading in a test piece

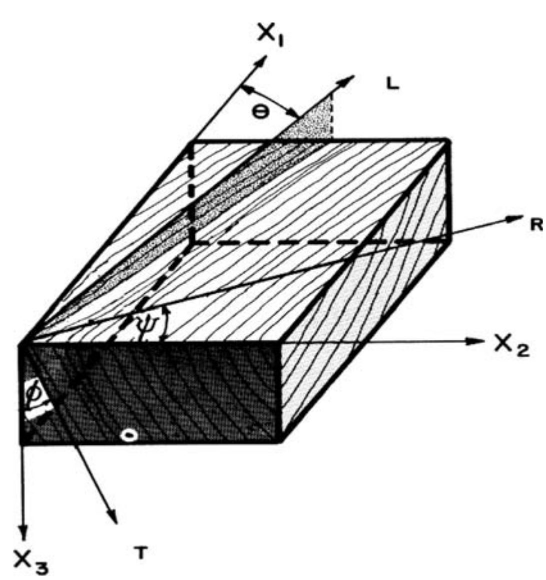

Fig. 3 Geometric (X_1, X_2, X_3) and orthotropic axes for a block of wood with cross grain. The angle θ is referred to as the "grain angle" [9]

Results

Static torsional test results for a hardwood with different grain orientations

For orthotropic materials such as wood, the grain angle (or grain orientation θ) in a block of wood has been

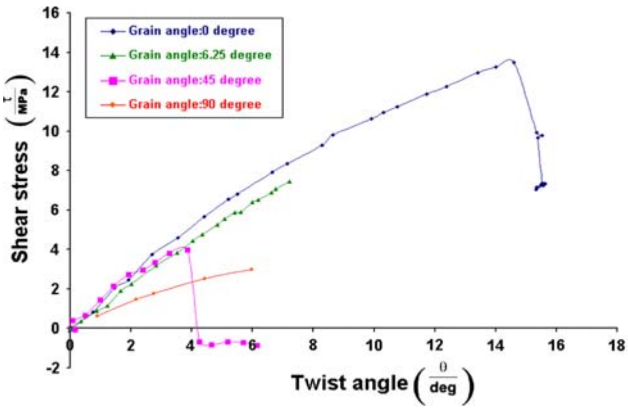

Fig. 4 Shear stress-twist angle curves for a hardwood with different grain orientations to the twist axis

illustrated by Bodig and Jayne [9] as shown in Fig. 3, using both the geometric (X_1, X_2, X_3) and orthotropic (L, R, T) axes. The grain angle is defined as the angle measured between the L- and X_1-axes. A series of static torsion tests were carried out on hardwood test pieces with grain orientations at 0°, 6°, 45° and 90° to the twist axis. The shear stress versus angle of twist plots for specimens with these grain orientations are shown in Fig. 4. The relationship between maximum shear stress and test-piece grain angle is presented in Fig. 5. All the curves indicate that under torsional loading failure in hardwood tends to be brittle. Comparing the curves for different grain orientations, Fig. 5 shows that the torsional strength of the hardwood decreases with increasing grain orientation. In Fig. 4 the slopes of the stress-twist angle curves for samples with different grain orientations are almost similar to each other except for the sample with a 90° grain angle which has a smaller slope.

Further torsional tests carried out on test pieces with a grain orientation at 90° to the longitudinal axis, but with the LT plane (longitudinal-tangential plane) and the LR plane (longitudinal-radial plane), respectively, perpendicular to the twist axis, revealed a difference in behaviour. This is shown in Fig. 3. When the LR plane is perpendicular to the twist axis, the maximum shear stress, at almost 3 MPa, is significantly higher compared with the test in which the LT plane is perpendicular to the twist axis, where the maximum shear stress is 2.3 MPa.

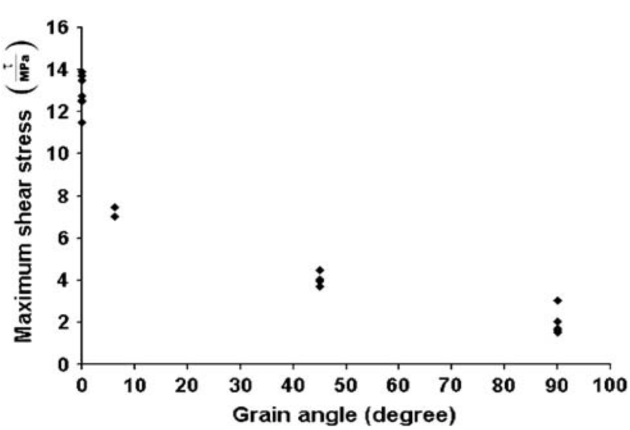

Fig. 5 Maximum shear stress versus grain angle to the twist axis for hardwood test pieces under static torsional loading

Fracture of hardwood in static torsional loading

The fracture characteristics in hardwood test pieces subjected to torsional loading vary with grain orientation. In test pieces where the grain orientation is 0°, 6° and 45° to the twist axis respectively, the crack leading to fracture propagates in the direction of the grain. When the grain is perpendicular to the twist axis, cracks developing in the LT or LR planes also develop along the grain direction (Figs. 6, 7).

For test pieces with the LT plane perpendicular to the twist axis, cracks propagate further in the direction perpendicular to the twist axis (tangential direction) than in the direction parallel to the twist axis (radial direction) (Fig. 8). In those cases where the LR plane is perpendicular to the twist axis, cracks develop over a shorter distance in the direction perpendicular to the twist axis (radial direction) than in the direction parallel to the twist axis (tangential direction) (Fig. 9). In those test pieces with a grain angle parallel, or nearly parallel to the twist axis, there is incomplete fracture at failure. The fracture appearance after a test piece was twisted through 180° showed multiple splintering along several grains parallel to the twist axis.

The cross-sections of hardwood test pieces, with a grain orientation parallel to the twist axis, were examined using optical microscopy. In Fig. 10, a crack nucleating and developing along the tangential direction can be seen.

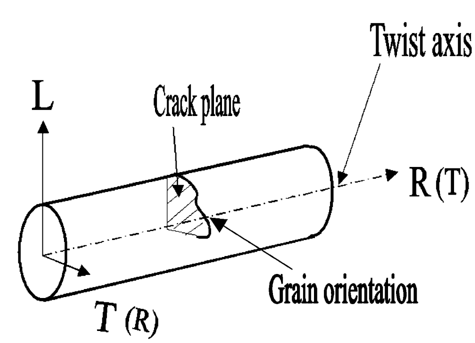

Fig. 6 Schematic diagram to illustrate the cracking orientation when the grain angle in a torsionally loaded test piece is perpendicular to the twist axis

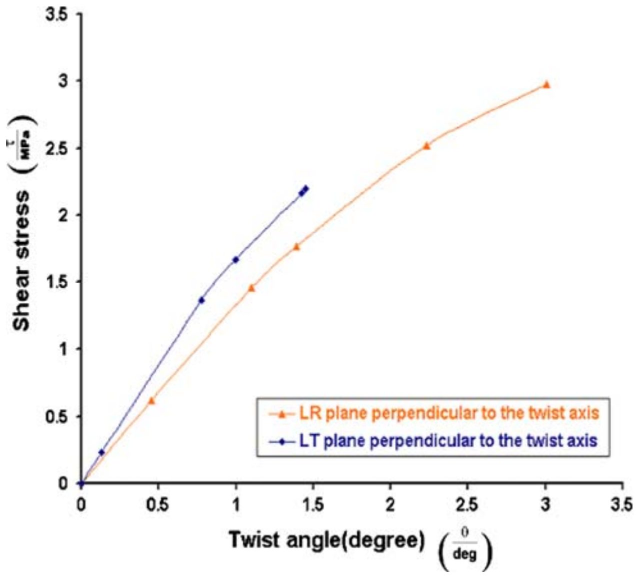

Fig. 7 Shear stress-twist angle curves for hardwood with a grain orientation perpendicular to the twist axis

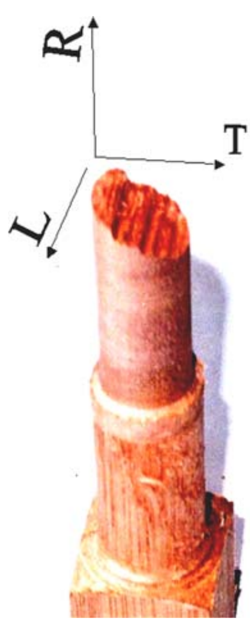

Fig. 8 Fracture surface of a hardwood sample with the *LT* plane perpendicular to the twist axis

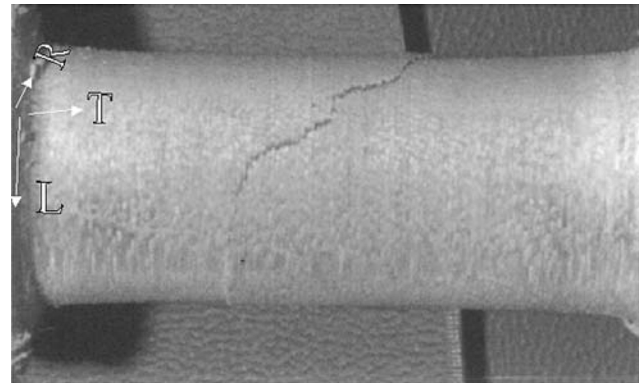

Fig. 9 A hardwood sample with the *LR* plane perpendicular to the twist axis

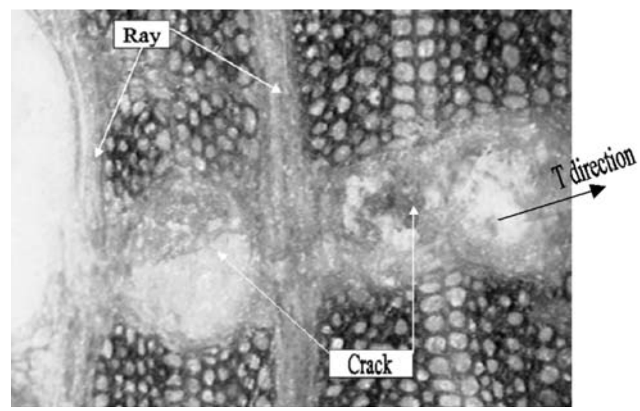

Fig. 10 A cross-section of a hardwood with grain orientation parallel to the twist axis (200×)

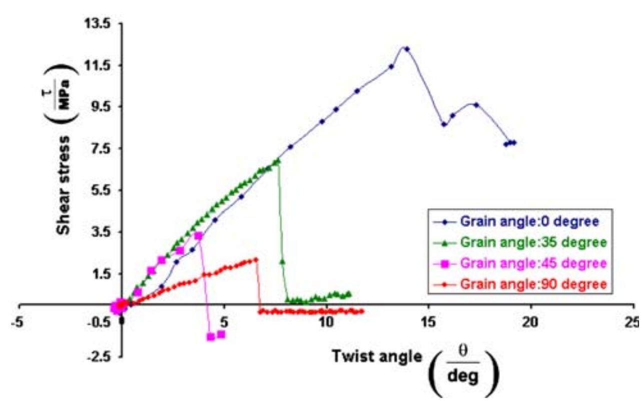

Fig. 11 Stress-twist angle curves for softwood with different grain orientations to the twist axis

Static torsional test results for a softwood with different grain orientations

The shear stress versus angle of twist plots for softwood specimens under static torsional loading with grain orientation at 0°, 35°, 45°and 90°, respectively, to the twist axis are shown in Fig. 11. Figure 12 shows the relationship between maximum shear stress and grain angle to the twist axis and similarly to the hardwood there is a decrease in torsional shear strength as the grain orientation increases. The sample with the grain perpendicular to the twist axis has a smaller slope compared with the other test pieces. A comparison of torsional strengths for samples with a 90° grain angle

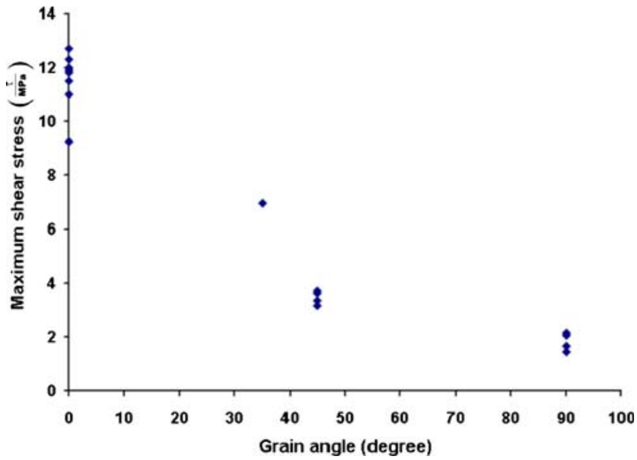

Fig. 12 Maximum shear stress versus grain angle to the twist axis for softwood under static loading

but with LT and LR planes, respectively, normal to the twist axis, Fig. 13, gave values of 2.05 and 2.16 MPa. This is different to the behaviour found in hardwood.

The results in Figs. 4 and 11 for hardwood and softwood, respectively, also suggest that the hardwood has a higher torsional strength. Crack development in softwood is not always along the grain direction. Usually a softwood sample with a 0° grain angle to the twist axis fails completely and cracks forming in planes parallel to the twist axis develop from one plane to another. But the failure pattern for softwood test pieces with a grain orientation at 90° to the twist axis is similar to that for hardwood except that for softwood, cracks develop over a longer distance in the radial direction. When the LR planes are perpendicular to the twist axis, the crack develops approximately perpendicular to the twist axis, along the LR plane; when the LT planes are perpendicular to the twist axis, 'staircase' cracks develop in a direction between 0° and 90° to the twist axis. For test pieces with a 45° grain angle, cracks propagate along the grain direction. For

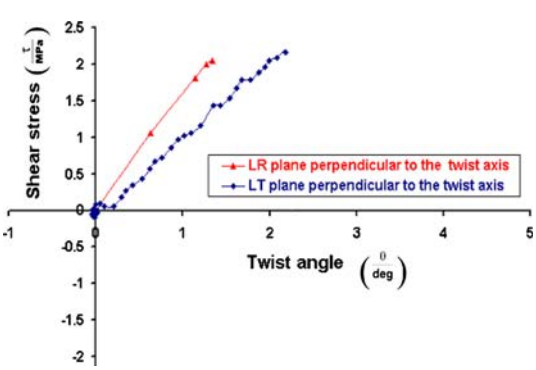

Fig. 13 Shear stress-twist angle curves for softwood with a grain orientation perpendicular to the twist axis

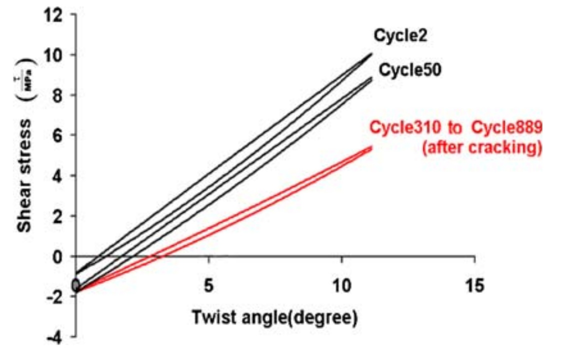

Fig. 14 Hysteresis loops for shear stress versus twist angle for a hardwood with grain angle parallel to the twist angle after different loading cycles. The twist angle is 11°

softwood test pieces with a grain orientation parallel to the twist axis, the crack originates and develops along a radial direction instead of a tangential direction.

Torsional fatigue of wood

The hysteresis loop for a hardwood

A series of hysteresis loops for hardwood with grains parallel to the twist axis at different stages in a fatigue test are plotted in Fig. 14 for pulsating twist between 0° and 11°. Figure 15 is the curve of maximum shear stress at each cycle versus cycle number. The loops for cycle 2 and cycle 50 are prior to crack formation whereas the loops for cycles 310 and 889 are, respectively, at crack initiation and after cracking has taken place, where cracking is indicated by a drop in load. The areas of the hysteresis loops are given in Table 1. The results show that before cracking occurs the hysteresis loop area and maximum shear stress at each

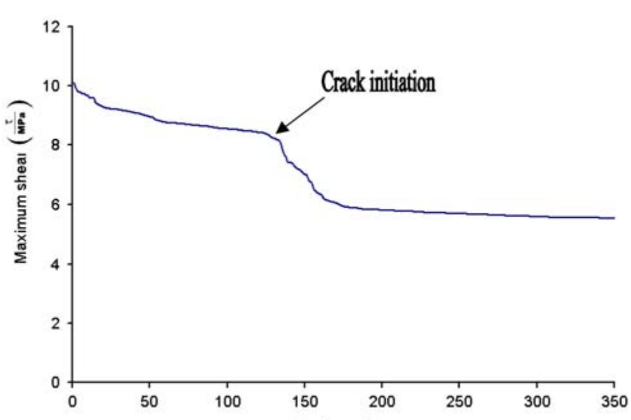

Fig. 15 Maximum shear stress versus cycle number for a hardwood with a grain angle parallel to the twist angle after different loading cycles. The twist angle is 11°

Table 1 Area and slope data for hardwood hysteresis loops

	Area of hysteresis loop (MPa × degree)	Slope of hysteresis loop (MPa/degree)	$\frac{\text{Area of hysteresis loop}}{\text{Slope of hysteresis loop}}$	Loop area/twist degree
Cycle 2	4.65	1.09	3.89	0.46
Cycle 50 (Just before crack formed)	4.15	1.03	2.38	0.41
Cycle 310(crack formed)	2.62	0.66	2.91	0.26
Cycle 889	2.29	0.61	3.23	0.23

cycle reduce with an increase in cyclic loading. This is a relaxation behaviour that has been reported by Bodig and Jayne [9] and Kollmann and Coté [10]. But the slope of the loop changes very little with an increase in loading cycles. After a crack appears both the loop area and slope decrease significantly, but hysteresis loops still exist. This indicates that even though the appearance of a crack causes a decrease in elastic stiffness, not all of the energy absorbed by the specimen is used up by non-elastic deformation and crack formation, but some is dissipated in other ways [11]. The failure is progressive rather than sudden.

The hysteresis loop for a softwood

Figure 16 shows a series of hysteresis loops for a softwood with grains parallel to the twist axis. The loops were recorded at cycles 2 and 52 prior to fracture and at cycle 53 when the specimen fractured. Table 2 shows the area of the hysteresis loops well before failure and just before failure. There are reductions in loop area and maximum shear stress with cycle loading that indicate the relaxation during fatigue (Figs. 16, 17).

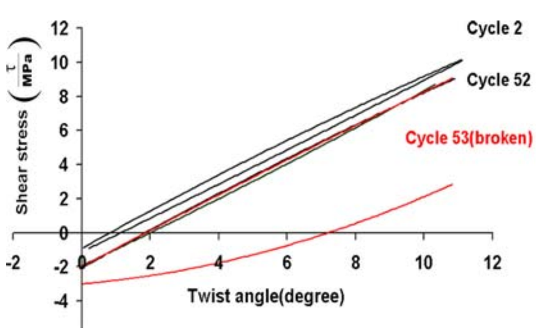

Fig. 16 Hysteresis loops for shear stress versus twist angle for a softwood after different loading cycles. The twist angle is 11°

The reduction in loop area between the initial cycles and the cycle just prior to failure is greater than that found in hardwood. At failure there is no hysteresis loop because the softwood specimens break completely. Also, before failure there is no detectable change in the slope of the loop.

A comparison of the hysteresis loops for a softwood and a hardwood

The hysteresis loop for the second loading cycle for a hardwood and softwood with grain parallel to twist axis are compared in Fig. 18 for the same twist angle. The lower slope of the hardwood indicates smaller test-piece stiffness. In most circumstances there is a smaller hysteresis loop area for the hardwood compared with the softwood, which indicates that the energy absorbed in softwood is greater than that in hardwood (Table 3). There is some variability in the data in Table 3 because test pieces were cut from different pieces of wood. However, samples were matched as closely as possible to minimise variability.

S–N curves for a hardwood and a softwood

The torsional fatigue tests were carried out under displacement control and pulsating cycling ($R = 0$). The results of torsional fatigue tests on both the hardwood and the softwood specimens, with a grain orientation parallel to the twist axis (0±0.5° to twist axis), are shown in Fig. 19. The data is presented as maximum shear stress versus log (cycles to failure) for loading in one direction. The maximum shear stress is defined as the maximum value in the first loading cycle, because relaxation during subsequent cycles leads to a fall in the torque required to maintain the angular displacement initially set. Failure in both the hardwood

Table 2 Area and slope data for softwood hysteresis loops

	Area of hysteresis loop (MPa × degree)	Slope of hysteresis loop (MPa/degree)	$\frac{\text{Area of hysteresis loop}}{\text{Slope of hysteresis loop}}$	Loop area/twist degree
Cycle 2	4.67	1.13	4.13	0.42
Cycle 52	1.51	1.13	1.34	0.14

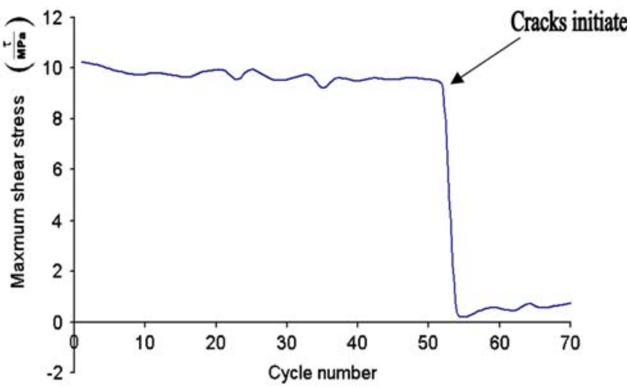

Fig. 17 Maximum shear stress versus cycle number for a softwood with grain angle parallel to the twist angle after different loading cycles. The twist angle is 11°

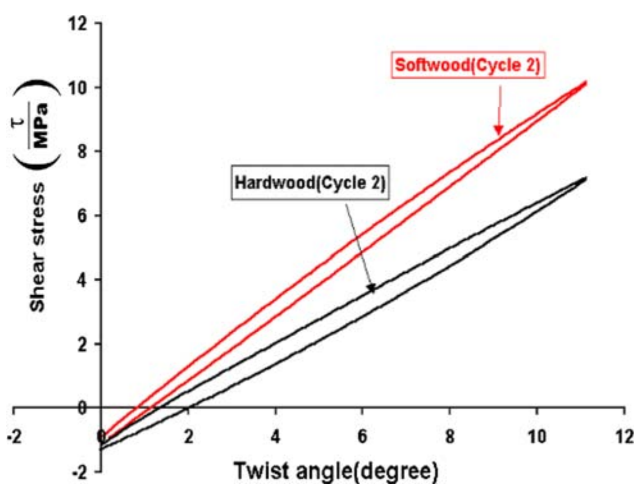

Fig. 18 Hysteresis loops for shear stress versus twist angle after the second loading cycle for a hardwood and a softwood. Twist angle for both test pieces is 11°

and the softwood specimens is defined as the point where there is a sudden fall in load at a particular loading cycle.

The maximum shear stress versus log (cycles to failure), or *S–N* plots, for the hardwood and softwood

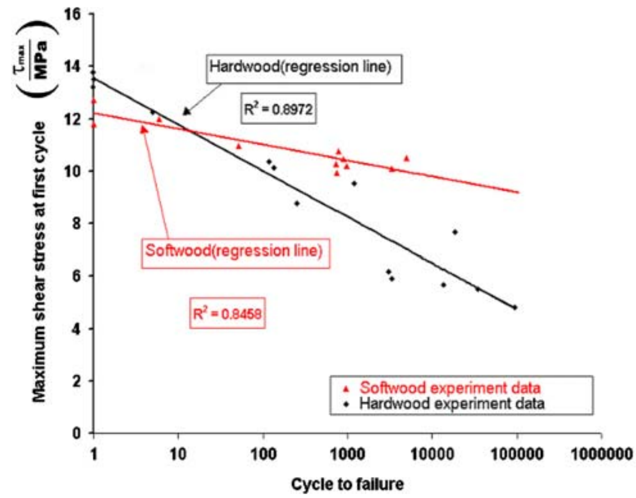

Fig. 19 *S–N* curves for both hardwood and softwood in cyclic torsional loading

are approximately linear and the gradient of the *S–N* curve for hardwood is larger than that for softwood (as shown in Fig. 19). This indicates that the torsional strength of the hardwood is affected more by fatigue than that of the softwood. Hardwood has higher torsional strength at static or low-cyclic torsional loading, and softwood has a higher strength at high-cyclic torsional loading. Since the tests were carried out in displacement control mode, which means that the relaxation influence on the fatigue strength is unavoidable, the twist angle is plotted against number of cycles to failure for both the hardwood and the softwood. The behaviour is similar to that for the *S–N* plots (Fig. 20). Comparison of Fig. 20 with Fig. 19 shows the effect of the greater stress relaxation of the hardwood than that of the softwood.

The influence of grain angle on the S–N curve

In order to investigate the influence of grain orientation on the maximum shear stress versus log (cycles to

Table 3 Area and slope data for a hardwood and a softwood hysteresis loop at cycle 2 for the same twist angle

	Area of hysteresis loop (MPa × degree)	Slope of hysteresis loop (MPa/degree)	$\frac{\text{Area of hysteresis loop}}{\text{Slope of hysteresis loop}}$	Loop area/twist degree
Hardwood sample 1	5.46	0.70	7.80	0.80
Hardwood sample 2	3.84	0.77	4.99	0.35
Hardwood sample 3	3.32	0.79	4.20	0.30
Hardwood sample 4	3.26	0.66	4.94	0.29
Hardwood sample 5	6.66	0.86	7.74	0.60
Softwood sample 1	9.74	1.16	8.40	0.88
Softwood sample 2	4.67	1.13	4.13	0.42
Softwood sample 3	6.42	1.28	5.02	0.58
Softwood sample 4	5.63	1.36	4.14	0.30
Softwood sample 5	7.48	1.51	4.95	0.67

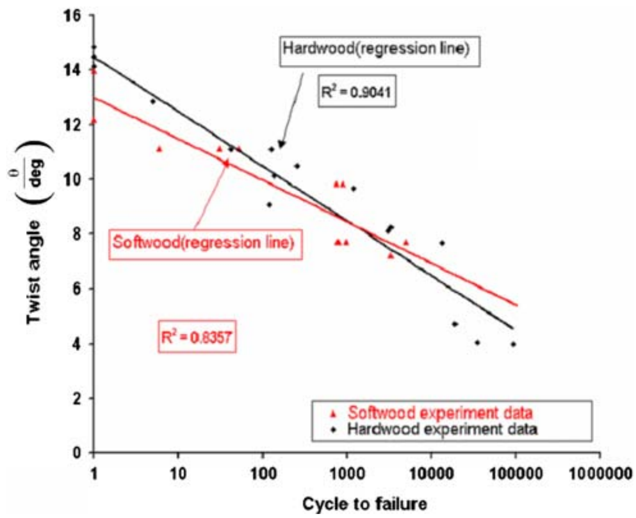

Fig. 20 Twist angle versus cycles to failure curves for both the hardwood and the softwood in cyclic torsional loading

failure), or *S–N* plots, a series of the hardwood samples with grain orientation at 2° to the twist axis were tested at different loads using the same experimental conditions as used for samples with their grain parallel to the twist axis. The *S–N* curves and twist angle versus cycles to failure curves for the 2° and parallel grain orientations are shown in Figs. 21 and 22, respectively. A linear regression analysis of the results shows that the *S–N* plot for the 2° grain orientation hardwood has a smaller gradient than the 0° orientation hardwood. This suggests that the fatigue behaviour is slightly poorer for the test piece with a 2° grain angle since the experimental data is below that for specimens with a 0° grain angle at shorter fatigue lives. Similarly the angle of twist versus cycles to failure behaviour is similar to that shown in the *S–N* plots but in this case the difference

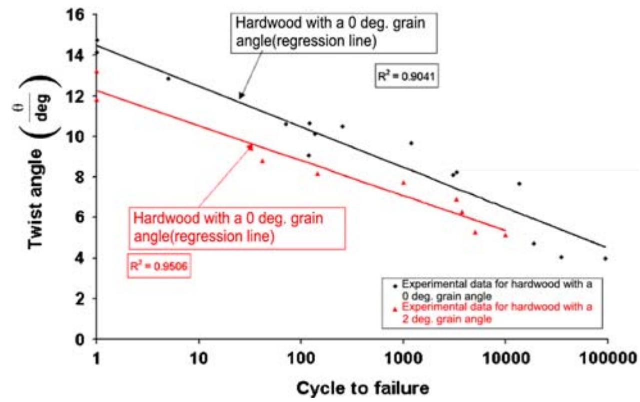

Fig. 22 Twist angle versus cycles to failure curves for hardwood with 0° and 2° grain angles to the twist axis

in slopes of the cycles to failure curves is smaller than that shown in the *S–N* curves. Since the graphical points on the angle of twist versus cycle to failure plot (Fig. 22), for the hardwood with a 2° grain angle, lie close to a straight line, it is the stress relaxation at high loads, shown by the ringed experimental points in Fig. 21, which causes experimental points to drop (it is considered that the relaxation will not affect the curve of twist angle versus cycle to failure).

Failure mode of the hardwood and the softwood

After fatigue failure, test pieces were sectioned and cracks were examined by eye and using a magnifying glass. In general, cracks in the hardwood propagated slowly. Most cracks developed parallel to the grain (Fig. 23), but there are some cracks which developed slightly obliquely to the grain. From observations of the cross-section by optical microscopy, cracks in the hardwood progressed into the test piece in the

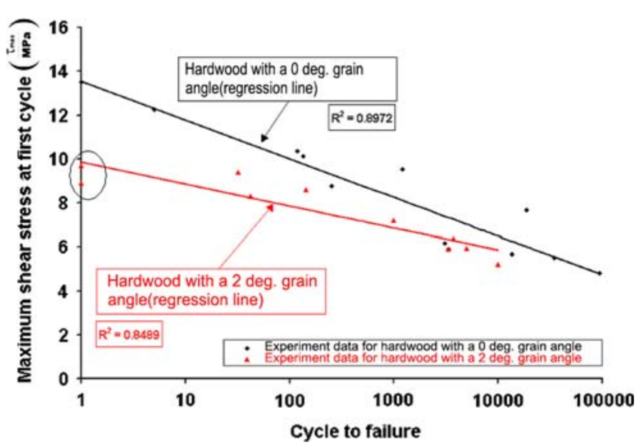

Fig. 21 *S–N* curves for hardwood with 0° and 2° grain angles to the twist axis

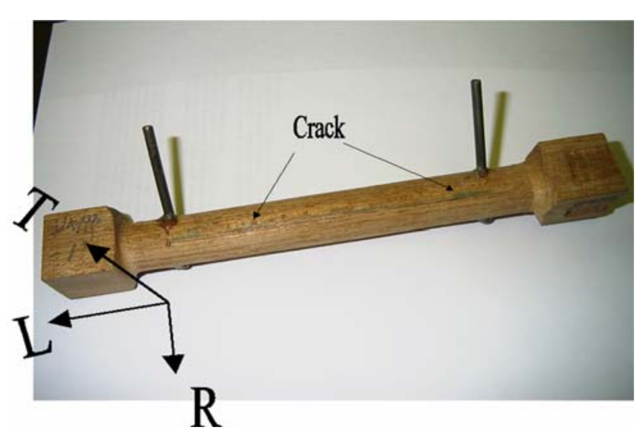

Fig. 23 Hardwood with a grain orientation parallel to the twist axis. The crack is indicated by dark the green colour

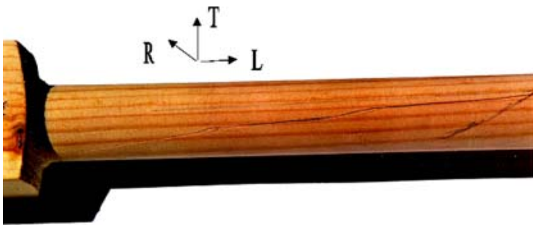

Fig. 24 Cracks in a softwood with grain parallel to twist axis

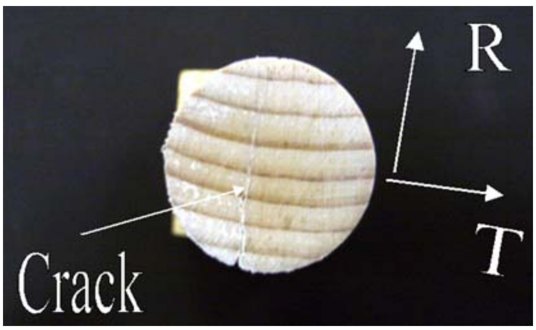

Fig. 25 Cracks in the cross-section of a softwood with the grain parallel to the twist axis. Cracking is perpendicular to the growth ring

tangential direction as was observed in the test pieces under static torsional loading (Fig. 10). Most cracks originated from the tensile and shear stress components which are present when the specimen has a 2–5° grain angle with the twist axis. This is understandable because wood cleaves easily in tension but not in compression. However, some cracks occurred along grains oriented at 2–5° which have a compressive stress component.

In a similar manner to test pieces under static torsional loading, most of the softwoods failed suddenly and with a rougher crack face compared with the hardwood. Observations of cross-sections under an optical microscope showed that cracks in the softwood developed along the radial direction (Figs. 24, 25).

Discussion of results

Results for wood under static torsional loading

It is known that there are two typical torsion failures in isotropic materials; brittle materials fail on planes of maximum tension that occur at 45° to the twist axis, ductile materials fail on the planes of maximum shear that occur parallel to and at 90° to the twist axis. This means that the material's properties and the stress state determine the fracture direction. But the experimental results for wood from this research show that wood always fails in the grain direction under static torsional loading. Kollmann and Coté [10] stated that the ultimate shearing strength for torsion parallel to the grain is related to the torsional properties and that the ultimate shear stress perpendicular to the grain is about 3–4 times higher than that parallel to grain. In his early work, Kollmann [12] shows that tensile strength will increase as the angle between the grain and tensile direction decreases. This means that the grain orientation will determine the fracture direction and fracture mode in wood. In these experiments, when the grain orientation is parallel or perpendicular to the twist axis during torsional testing, the plane of the grain will be in pure shear. But the torsional strengths on these two planes are different because of the orthotropic properties in wood. The slope of stress versus twist angle curves of these two planes are also different, which usually corresponds to the modulus of rigidity (Figs. 4 and 11). This can probably be explained using the stress, strain and shear modulus relationships for orthotropic materials. The relationships for a sample's diameter d, length l, twist angle φ, maximum shear stress $\tau_{\max}$, maximum shear strain γ_s, shear modulus G_{LR} or G_{LT} and combined shear modulus $\bar{G}$ are given by the following equations[9]:

$$\gamma_s = \frac{\varphi \cdot d}{2 \cdot l} \tag{1}$$

$$\tau_{\max} = \bar{G} \cdot \gamma_s \tag{2}$$

$$\bar{G} = \frac{2 \cdot G_{LR} \cdot G_{LT}}{G_{LR} + G_{LT}} \tag{3}$$

The properties of the hardwood red lauan and the softwood sitka spruce used in this research have been measured and are shown in Table 4. According to these data, the effective shear modulus of a hardwood sample with a grain orientation parallel to the twist axis is 0.42 GPa, and the combined shear modulus of a hardwood test piece having a grain orientation perpendicular to the twist axis is 0.05 GPa. We know that if both samples fail at the same twist angle corresponding to some shear strain γ, the torsional shear strength ($\tau_{\max}$) of the sample having a grain orientation at 90° to the twist axis is weaker than the sample having a grain orientation at 0° to the twist axis (calculations show that the torsional shear strength of a sample with a 90° grain angle is just 28% of that for the sample with a 0° grain angle). Actually, the former sample failed at a smaller twist angle than the latter one (Fig. 4 shows that the torsional shear strength of a sample with a 90° grain angle is just 20% of that for a

Table 4 Elastic modulus, modulus of rigidity and density of light red lauan and sitka spruce (means of three measurements)

	G_{LT} (GPa)	G_{LR} (GPa)	G_{RT} (GPa)	E_L (GPa)	E_T (GPa)	E_R (GPa)	Density (kg m^{-3})	Moisture content
Light red lauan (data from this experiment)	0.62	0.68	0.08	7.38	0.22	0.34	430–438	5.8–6.3%
Sitka spruce(data from this experiment)	0.52	0.48	0.05	7.22	0.34	0.29	457–469	6.5–8.3%

Table 5 Modulus of rigidity of test pieces with different grain angle (taken from Figs. 1, 7)

	Hardwood				Softwood			
Grain angle (°)	0	6.25	45	90	0	35	45	90
Modulus of rigidity (GPa)	0.18	0.20	0.20	0.10	0.32	0.28	0.27	0.11

sample with a 0° grain angle). Another possible explanation is that crack growth rates vary for the different systems of crack development. The gradient will increase more quickly when a crack is perpendicular to the twist axis and increase more slowly if the crack is parallel to the twist axis. So the crack perpendicular to the twist axis is more unstable during growth. Using the data in Figs. 4 and 11, the modulus of rigidity corresponding to the grain orientation has been determined and is shown in Table 5. It shows that when the grain orientation is perpendicular to the twist axis, both hardwood and softwood will have the smallest modulus of rigidity.

It is interesting that the stress-twist angle curves for samples with a 0° grain angle show some non-linearity prior to the fall off in stress at failure. Dinwoodie [13] has mentioned that wood will strain almost linearly with stress when it is tested in compression, tension or bending although a reduction in the gradient of the stress–strain curve occurs at high loads. The results from this study for test pieces tested in torsion, but with grains not parallel to the twist axis are consistent with this previous work. However, when the grain orientation is parallel to the twist axis, the stress-twist angle behaviour becomes non-linear before final failure (Figs. 4, 11).

Usually, the fracture of materials is described in terms of three principal modes, as illustrated in Fig. 26. The crack mode should be a combination mode when two propagating directions for a cracking plane are considered [14]. For the hardwood samples with grains parallel to the twist axis, the cracks propagate in the II_{RL} and III_{RT} modes (Fig. 27). The mode of cracking for hardwood samples with a 45° grain angle is closer to a I_{RT} and I_{RL} modes considering that the plane of the grain is subjected to tensile stress (Figs. 28, 29). The crack mode for a softwood sample with its grain parallel to the twist axis seems more close to II_{TL} and III_{TR} modes when the crack develops along the grain

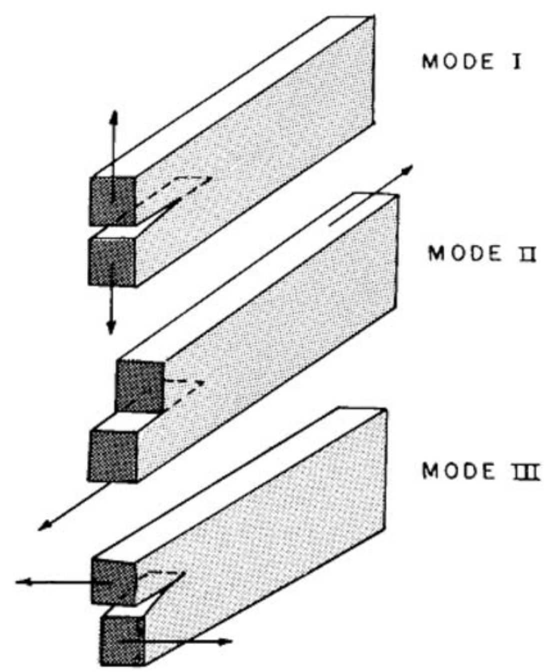

Fig. 26 Modes of fracture: mode I, opening cleavage; mode II, forward shear; mode III, transverse shear [9]

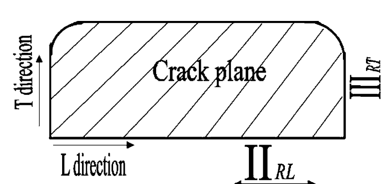

Fig. 27 Combined cracking mode in a hardwood with a 0° grain angle

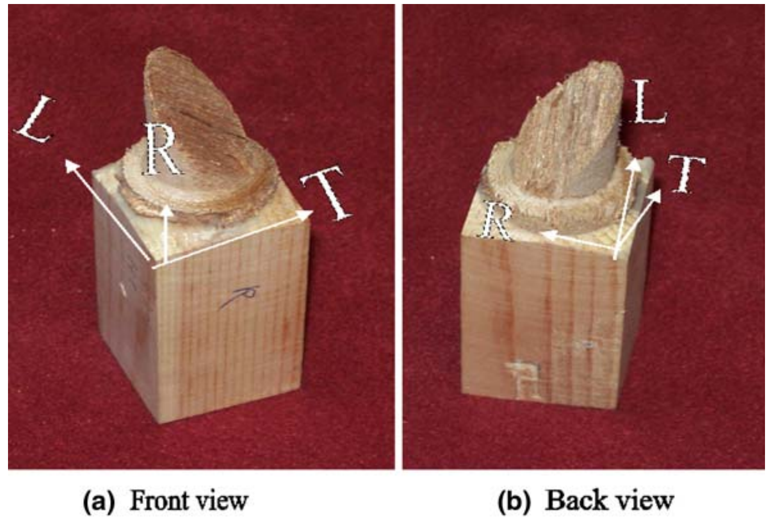

Fig. 28 Fracture surface of a hardwood sample with a grain orientation at 45° to the twist axis. Here *L* is the longitude direction, *R* is the radial direction and *T* is the tangential direction

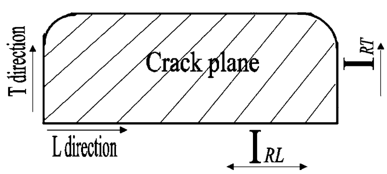

Fig. 29 Combined fracture mode in a hardwood with a 45° grain angle

direction in the longitudinal direction. The crack mode for a softwood sample with a 45° grain angle is closer to I_{TR} and I_{TL} modes. A summary of fracture modes for the samples having different grain angles is presented in Table 6.

Results for wood under torsional fatigue loading

It is interesting that hardwood has a higher torsional strength at static or low-cyclic torsional loading, and softwood has a higher strength at high-cyclic torsional loading. It is difficult to explain this phenomenon using the wood properties listed in Table 4, although the fact that the density of the softwood is higher than that of the hardwood probably explains this. The result is consistent with the findings of Sekhar and Sukla [6]. The maximum number of cycles reached in this research is 100,000, but no fatigue limit has been observed in either the hardwood or the softwood. If there were torsional fatigue limits, it seems from their *S–N* curves that softwood should have a higher fatigue limit than that of hardwood. The tendency of the twist angle against number of cycles to failure curve is almost similar to that of the *S–N* curve and this indicates that the control mode for torsional fatigue testing does not affect the result in this respect.

In a similar way to its behaviour in static torsional testing, hardwood fails gradually and incompletely in cyclic testing, and the cracks develop along the tangential direction instead of the radial direction. Softwood fails suddenly and completely and the cracks develop along the radial direction. This result is also confirmed by the stress-twist angle hysteresis loop data which showed that the hysteresis loop for hardwood still persisted after cracks appeared and the loop for

Table 6 The relationship between grain angle, fracture mode and torsional strength

Type of wood	Grain angle	Torsional strength (MPa)	Fracture mode	Stress component
Hardwood	0°	12.91±1.41	II_{RL} and III_{RT}	Shear stress component
	45°	4.04±0.43	I_{RL} and I_{RT}	Tensile stress component
	90°	1.98±1.06	II_{RL}, III_{RT} and III_{TR} or II_{TL}, III_{TR} and III_{RT}	Shear stress component
Softwood	0°	11.56±1.14	II_{TL} and III_{TR}	Shear stress component
	45°	3.47±0.30	I_{TL} and I_{TR}	Tensile stress component
	90°	1.83±0.39	II_{TL}, III_{TR} and III_{RT} or II_{RL}, III_{RT} and III_{TR}	Shear stress component
Softwood with a knot	0° (cracking at 30–60° cross grain angle)	11.63±2.44	I_{TL} and I_{TR}	Tensile component

softwood disappeared after the sample's failure. This means that the hardwood still absorbs energy after cracking occurs.

The higher slope of the stress-twist angle loop for softwood compared with that for hardwood is consistent with observations from static torsional testing. In the fatigue test, this tendency is more apparent. Considering that the softwood has absorbed more hysteresis energy during testing than the hardwood, it is reasonable to assume that the vessels in hardwood make it less stiff than softwood, or that it is affected by density.

Since earlier fatigue work carried out by other researchers was focused on bending, tensile and shear loading [1, 15], the *S–N* curves, presented in this work for the hardwood (red lauan) and the softwood (Sitka spruce), provide a guide for design under the conditions used in this work. The shallower gradient of the *S–N* curve for the softwood indicates that the softwood is more resistant to torsional fatigue failure than the hardwood if both grain orientations are parallel to the twist axis.

The influence of grain orientation on the torsional fatigue of wood

The results of this research (Figs. 21, 22) show that a grain angle which is not parallel to the twist axis will weaken the static and low cyclic torsion strength. The high cyclic torsional strength of a sample with a non-parallel grain orientation is close to that of the sample with a grain orientation parallel to the twist angle. This result agrees with the findings of Lewis [16] when he compared straight grained specimens with specimens having a grain orientation of $\tan^{-1} 1/12$ (equal to 4.8°) with the longitudinal axis in bending fatigue. He found that straight grained specimens have slightly higher fatigue strengths although for green wood specimens the reverse was found. It seems that the high-cyclic torsional strength is not affected by the grain angle of the wood.

Conclusions

1. The results of static torsional tests show that the static torsional strength for both hardwood and softwood will decrease as the grain orientation of a sample increases from 0° to 90°. Visual and microscopic observations indicate that the failures of both hardwood and softwood with a 0° grain angle to the twist axis are incomplete. There is a non-linearity prior to the final dramatic drop in stress-twist angle curves for both hardwood and softwood samples with a grain parallel to the twist axis. Hardwood is stronger than softwood in static torsional loading.
2. The results of static torsional testing show that the modulus of rigidity will change with different grain orientation in a wood test piece. For both hardwood and softwood, the test pieces with a 90° grain angle to the twist axis have the smallest modulus of rigidity.
3. The failure modes for both hardwood and softwood with a 90° grain angle to the twist axis are either a combination of mode II_{RL}, mode III_{RT} and III_{TR} if the *LR* plane is perpendicular to the twist axis, or a combination of mode II_{TL}, mode III_{TR} and III_{RT} if the *LT* plane is perpendicular to the twist axis. The failure mode for hardwood with a 45° grain angle to the twist axis is mode I_{RL} and I_{RT}. The failure mode for softwood with a 45° grain angle to the twist axis is mode I_{TL} and I_{TR}. The failure mode for hardwood with a 0° grain angle to the twist axis is mode II_{RL} and III_{RT}., but fracture is incomplete. The failure mode for softwood with a 0° grain angle to the twist axis is a combination of mode II_{TL}, II_{LT} and III_{TR} , and final fracture is sudden and complete.
4. The hysteresis loops deriving from cyclic loading show that softwood has a greater energy dissipation than hardwood during early cyclic torsional loading. There is also more energy dissipation prior to the appearance of a crack compared with hardwood. However, the hardwood shows a small decrease in stiffness with each loading cycle prior to failure, whereas the stiffness of the softwood only changes slightly before failure. The grain angle in a hardwood has only a small influence on the hysteresis loop.
5. From a comparison of their *S–N* curves, it has been shown that fatigue has more influence on the torsional strength of hardwood than softwood. The grain angle in hardwood has less influence on the high cyclic torsional strength than the static or low cyclic torsional strength at low grain angles.
6. Visual and microscopic observations show that the cyclic damage caused by torsional loading in hardwood is gradual whereas in softwood failure occurs by sudden crack propagation. This is supported by the hysteresis loop for stress and strain during cracking, where the loop is broken and disappears during and after cracking takes place in a softwood but just becomes smaller during cracking in a hardwood. The crack growth is along the tangential direction in hardwood and the radial direction in softwood (Figs. 10, 25).

7. Under both static and fatigue torsional loading, cracks in a hardwood sample with a 0° grain angle to the twist axis propagate along the grain direction in planes parallel to twist axis and nucleate and develop preferentially in a tangential direction in the cross-section. Cracks in a softwood sample with a 0° grain angle to the twist axis nucleate and develop preferentially in a radial direction in the cross-section, but they do not propagate only along the grain direction in the planes parallel to the twist axis, but cross from one plane to another.

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