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The toughness of secondary cell wall and woody tissue

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SUMMARY

The 'across grain' toughness of 51 woods has been determined on thin wet sections using scissors. The moisture content of sections and the varying sharpness of the scissor blades had little effect on the results. In thin sections (< 0.6 mm), toughness rose linearly with section thickness. The intercept toughness at zero thickness, estimated from regression analysis, was proportional to relative density, consistent with values reported for non-woody plant tissues. Extrapolation of the intercept toughness of these woods and other plant tissues/materials to a relative density of 1.0 predicted a toughness of 3.45 kJ m^{-2}, which we identify with the intrinsic toughness of the cell wall. This quantity appears to predict published results from K_{IC} tests on woods and is related to the propensity for crack deflection. The slope of the relationship between section thickness and toughness, describing the work of plastic buckling of cells, was not proportional to relative density, the lightest (balsa) and heaviest (lignum vitae) woods fracturing with less plastic work than predicted. The size of the plastic zone around the crack tip was estimated to be 0.5 mm in size. From this, the hypothetical overall toughness of a thick (> 1 mm) block of solid cell wall material was calculated as 39.35 kJ m^{-2}, due to both cell wall resistance (10 %) and the plastic buckling of cells (90 %). This value successfully predicts the toughness of most commercial woods (of relative densities between 0.2 and 0.8) from 'work area' tests in tension and bending. Though density was the most important factor, both fibre width/fibre length (in hardwoods) and lignin/cellulose ratios were negatively correlated with the work of plastic buckling, after correcting for density. At low densities, the work of plastic buckling in the longitudinal radial (LR) direction exceeded that in longitudinal tangential (LT), but the reverse was true for relative densities above 0.25. This could be attributed to the direction of rays. Density for density, the toughness of temperate hardwoods tested was about 20 % lower than that of tropical hardwoods. This is probably due to the much greater number of vessels in temperate hardwoods. Vessels appear either not to display buckling behaviour during fracture at all or to collapse cheaply. These general results have applications to other plant tissues.

1. INTRODUCTION

It appears that when a crack propagates perpendicular to the long axis of wood fibres or tracheids (i.e. across the grain), work is done in three ways: (i) in fracture of cell walls, (ii) in the plastic buckling of these walls into the cellular lumina by shear stresses (which spread small fractures between microfibrils of the S2 layer on either side of the main crack) and (iii) in pull-out of whole cells produced by crack deviation. The first cause is probably of low cost (but has never been evaluated), whilst the last-named factor has been calculated to contribute little (Jeronimidis 1980). It is plastic buckling to which woody toughness is attributed (Gordon & Jeronimidis 1974, 1980; Jeronimidis 1980). When fibres (hardwoods) or tracheids (softwoods) are subjected to tensile stresses, the helical windings of the cellulosic microfibrils in the S2 layer of their secondary cell walls (the thickest wall layer in most woods; Dinwoodie 1981; Bodig & Jayne 1982; Fengel & Wegener 1989) produce shear stresses that tend to make the cell rotate (Pagano *et al*. 1968). Constraints around these cells prevent this rotation, and the resultant instability, even at low strains, causes the walls to buckle into the lumen, the effect depending on the angle of microfibril lay-up (Page *et al*. 1971). This effect may be restricted to cells through which the main crack passes but, despite this, Jeronimidis (1980) argues that most of the toughness of woods derives from work done in this way. Macrocellular models have been made with helically wound walls. These have an extremely high toughness which, if ideally organized, reaches 0.4 MJ m^{-2} (Gordon & Jeronimidis 1974; Jeronimidis 1980), which makes this one of the most potent toughening mechanisms ever discovered.

Little work appears to have been done, however, on this postulated mechanism in woods themselves, partly due to uncertainty about how to calculate toughness. The toughness of woods in 'work area' tests, extrapolated from low and medium density woods to a hypothetical wood with solid cell walls, has been estimated by Jeronimidis (1980) and Gordon & Jeronimidis (1980) as 40–60 kJ m^{-2}. However, the equivalent, derived from a K_{IC} test, is only 1.65 kJ m^{-2} (Ashby *et al*. 1985), though this is extrapolated from the behaviour of low-density balsa. It is generally supposed that the reason for this is that K_{IC} tests exclude plastic work, calculations being based only on the force at which a fracture initiates from a sharpened notch, a risky procedure with a heterogeneous solid (though it has been proved that the initial crack from a notched specimen does indeed pass across the cell

Table 1. *Summary of woods used in this study and their densities*

wood (common name in roman; taxonomic name in italics with authority)	origin	density (kg m^{-3})
Balau *Shorea* sp. (Section *Shorea*) (Dipterocarpaceae)	tropical	800
Balsa *Ochroma lagopus* Sw. (Bombacaceae)	tropical	140, 255
Belian *Eusideroxylon zwageri* Teijsm & Binn. (Lauraceae)	tropical	910
Bigtooth aspen *Populus grandidentata* Michx. (Salicaceae)	temperate	480
Bintangor *Calophyllum* sp. (Guttiferae)	tropical	480
Bitis *Madhuca utilis* (Ridl.) Lam (Sapotaceae)	tropical	1050
Canadian yellow birch *Betula alleghaniensis* Britt. (Betulaceae)	temperate	745
Chengal *Neobalanocarpus heimii* (King) Ashton (Dipterocarpaceae)	tropical	880
Dark Red Meranti *Shorea* sp. (Sections *Brachypterae*, *Mutica*, *Pachycarpae*) (Diperocarpaceae)	tropical	480
European Hornbeam *Carpinus betulus* L. (Betulaceae)	temperate	755, 845
Giam *Hopea* sp. (Dipterocarpaceae)	tropical	960
Jelutong *Dyera costulata* Hook. f. (Apocynaceae)	tropical	380
Kasai *Pometia* sp. (Sapindaceae)	tropical	880
Kekatong *Cynometra* sp. (Leguminosae)	tropical	1080
Keledang *Artocarpus* sp. (Moraceae)	tropical	720
Kempas *Koompassia malaccensis* Maing. ex Benth. (Leguminosae)	tropical	800
Keruing *Dipterocarpus* sp. (Dipterocarpaceae)	tropical	945
Kulim *Scodorocarpus borneensis* (Baillon) Becc. (Olacaeae)	tropical	900
Kungkur *Albizia* or *Archidendron* sp. (Leguminosae)	tropical	620
Lignum vitae *Guaiacum sanctum* L. (Zygophyllaceae)	tropical	1360, 1395
Lignum vitae *Guaiacum officinale* L. (Zygophyllaceae)	tropical	1340
Light red meranti *Shorea* sp. (Sections *Brachypterae*, *Mutica*, *Pachycarpae*) (Dipterocarpaceae)	tropical	500
Machang *Mangifera* sp. (Anacardiaceae)	tropical	560
[a]Maidenhair *Ginkgo biloba* L. (Ginkgoaceae)	temperate	470, 505
[a]Malayan kauri *Agathis borneensis* Warb. (Araucariaceae)	tropical	510
Melunak *Pentace* sp. (Tiliaceae)	tropical	770
Mempisang (Annonaceae)	tropical	570
Meranti Bakau *Shorea uliginosa* Foxw. (*Dipterocarpaceae*)	tropical	720
Merawan *Hopea* sp. (Dipterocarpaceae)	tropical	690

Table 1. (*cont.*)

wood (common name in roman; taxonomic name in italics with authority)	origin	density (kg m^{-3})
Merbau *Intsia palembanica* Miq. (Leguminosae)	tropical	630
Paper Birch *Betula papyrifera* Marshall (Betulaceae)	temperate	655
Penarahan (Myristacaceae)	tropical	720
[a]Pencil Cedar *Libocedrus decurrens* Torr. (Cupressaceae)	temperate	410
Perupok *Lophopetalum* sp. (Celastraceae)	tropical	890
Pulai *Alstonia* sp. (Apocynaceae)	tropical	330
Punah *Tetramerista glabra* Miq. (Tetrameristaceae)	tropical	730
Ramin *Gonystylus bancanus* (Miq.) Kurz (Thymelaceae)	tropical	770
Red Balau *Shorea* sp. (Section *Shorea*) (Dipterocarpaceae)	tropical	890
[a]Redwood *Sequoia sempervirens* (D. Don) End1. (Taxodiaceae)	temperate	425, 485
Resak *Cotylelobium* or *Vatica* sp. (Dipterocarpaceae)	tropical	980
Rubber wood *Hevea brasiliensis* (A. Juss.) Muell. -Arg. (Euphorbiaceae)	tropical	680
Sepetir *Sindora* sp. (Leguminosae)	tropical	690
Sesendok *Endospermum diadenum* (Miq.) Airy Shaw (Leguminosae)	tropical	550
Simpoh *Dillenia* sp. (Dilleniaceae)	tropical	600
Teak *Tectona grandis* L.f. (Verbenaceae)	tropical	720
Tembusu *Fragraea* sp. (Loganiaceae)	tropical	600
Terap *Artocarpus* sp. (Moraceae)	tropical	440
Terentang *Campnosperma* sp. (Anacardiaceae)	tropical	310
Trembling Aspen *Populus tremuloides* Michx. (Salicaceae)	temperate	430
Tualang *Koompassia excelsa* (Becc.) Taubert (Leguminosae)	tropical	770
Yellow Meranti *Shorea* sp. (Section *Richetioides*) (Dipterocarpaceae)	tropical	470

[a] Softwood.

wall; Ashby *et al*. 1985). If this explanation is correct, then comparing the work area with K_{IC} test results above suggests that the plastic work done in the Gordon–Jeronimidis mechanism contributes most of the work of fracture. We cannot know, however, unless the work done by each mechanism can be isolated.

In this study, we have attempted to examine factors associated with the work of fracture of woods by scissor tests. These tests effectively prevent the deviation of the main crack from a path directly across the grain. Pull-out of whole cells is, therefore, almost totally suppressed. Fracture depends only on plastic buckling and cell wall fracture. By manipulating the conditions of scissor tests, it is possible to separate fracture of the cell wall from the work of plastic buckling. The tests can be carried out quickly on small pieces of wood and are, arguably, more reliable than the notched tensile or three-point bending tests normally employed because they are not subject to the macroscopic variation in properties seen commonly even within one normal-sized test specimen. However, because their loading geometry is very different from tensile or bending tests, it must be demonstrated that the fracture mechanisms seen in standard tests are expressed in cutting.

It is the purpose of this paper to show that cutting tests produce comparable toughness values to other tests and that they have the analytical power to evaluate the contributions of cell wall fracture and plastic buckling to wood toughness. Most of the woods tested here are tropical woods. These are easier to test than temperate woods because they do not usually contain growth rings (reflecting phasic changes in density). However, several temperate woods are included as a comparison, because the properties of these woods are much better known than those of tropical woods.

2. MATERIALS AND METHODS

Fifty-one woods were tested, with five woods being tested at two different densities (table 1). Small blocks, measuring a few cubic centimetres, were cut from samples of Malaysian woods housed in the collection of the School of Biological Sciences, The National University of Singapore. (These originate from samples supplied by the Forestry Research Institute, Malaysia (FRIM).) The data set was supplemented by balsa (obtained commercially in Singapore), temperate woods and lignum vitae (from A. B. Green, A. N. Curtis and Regis Miller). Data on the morphology of 27 Malaysian hardwoods were taken from Peh *et al.* (1986), supplemented by data on balsa (Easterling *et al.* 1982). Chemical compositions were also from Peh *et al.* (1986) with additional unpublished data from FRIM sent by K. C. Khoo. Values for temperate woods, teak and balsa were taken from Fengel & Wegener (1989).

The density of the wood blocks, in kg m^{-3}, was measured by weighing these blocks and then displacing them in water (attaching a weight of known volume when necessary) to obtain their volume. For some woods, this was checked by measuring the dimensions of the block and then weighing. Densities were converted to relative densities by dividing by 1500 (Gibson & Ashby 1988). Thin uniform sections, ranging in thickness from 0.05–3.0 mm (generally < 0.6 mm for most woods), were cut from these blocks in both longitudinal–tangential (LT) and longitudinal–radial (LR) directions using a diamond wheel rotating at 2800 rpm (Mok & Fearnhead 1985).

These sections, saturated with water, were then placed under the upper blade of a pair of Dovo (Germany) hairdressing scissors (radius of edge sharpness, r_e, 1.6 μm). These scissors were mounted on a portable testing machine, fitted with a load cell, displacement encoder and motor drive (Darvell *et al.* 1996). During tests, the crosshead speed moved against the handle of the lower scissor blade at 14 mm $\min^{-1}$, driving the blade to cut directly across the grain of the specimen, in either an LR or LT direction. Owing to the lever arrangement of the scissors, average cutting speeds were higher than that of the crosshead, being 20–30 mm $\min^{-1}$. The average offcut width was between 2 and 5 mm. This testing method generally produced stable fracture unless specimens were very thick, when crack growth became difficult to control. After testing, the thickness of each section was measured with a thickness gauge and the length of cut with dial calipers. The average sample size for each direction of cut in each wood was 20. To test the generality of the results, dark red meranti was also cut using very blunt scissors (Delica Lion ceramic scissors; $r_e = 12.5$ μm). Belian and balsa sections were re-tested after drying at 60 °C for 12 h. The results of over 2500 toughness tests are reported here. Least-squares regression is used throughout this paper.

In order to test specific predictions about plastic buckling (see §4), several modifications to the above procedures were run. In addition to cuts at 90° to the grain, dark red meranti was cut wet at 45° and 10° to the grain. Very thin 0.03–0.04 mm sections were made of bitis wood. These had a thickness of the order of the fibre diameters within this wood (Peh *et al.* 1986). Such sections would, therefore, be expected to possess, on average, a lot of fragmented cells that lack a complete circumference. These sections were then layered to produce an overall specimen thickness matching those of specimens that consisted solely of individual sections. These two sets of specimens were tested and their toughness compared.

A sample of cut surfaces of 124 specimens from 13 woods, covering the full range of densities shown in table 1, was observed under a Cambridge S440 scanning electron microscope after air-drying.

3. RESULTS

The profile of fibres or tracheids seen at the fractured surfaces of post-test specimens of most woods showed clearly that these had permanently buckled during cutting (figure 1). The centre of the fracture surface was roughened. Measurements on micrographs of 124 specimens showed this rough area to average one-third (mean 0.335; s.d. 0.054) of section thickness. This did not vary significantly with either section thickness itself or wood density. On either side of this roughened zone, the fracture surfaces were smooth, typical of slow fracture (figure 1). These sometimes showed knife marks indicating the direction of travel of the blade. One of these smooth surfaces lay in the same plane as the rough area; the other was at a slight angle (figure 1). The only exceptions to this appearance were the lightest woods, in which the roughened area was not so pronounced. In particular, in balsa, most cells had not buckled, retaining their intact circular or hexagonal profile (figure 2*a*). In lignum vitae, the densest wood tested, changes appeared to be limited by the narrow lumen (figure 2*b*). The vessels in the hardwood specimens had generally collapsed (figure 1).

The toughness of wet wood specimens was linearly related to section thickness up to at least 0.6 mm. For a light wood, jelutong, in which crack growth could be controlled, the linear relation held until 1.0 mm thickness, after which there was a gradually decreasing slope (figure 3). There was little difference in results between wet and dry specimens (e.g. belian; figure 4*a*). The effect of using very blunt scissors versus sharp ones was to increase toughness by about 15–37% (figure 4*b*).

For each wood, the toughness at zero thickness (in kJ m^{-2}, termed the intrinsic toughness) and the slope relating toughness to section thickness (in MJ m^{-3}, termed plastic work) was calculated by least-squares regression. These values were then plotted against relative density. In figure 5*a*, results are shown for

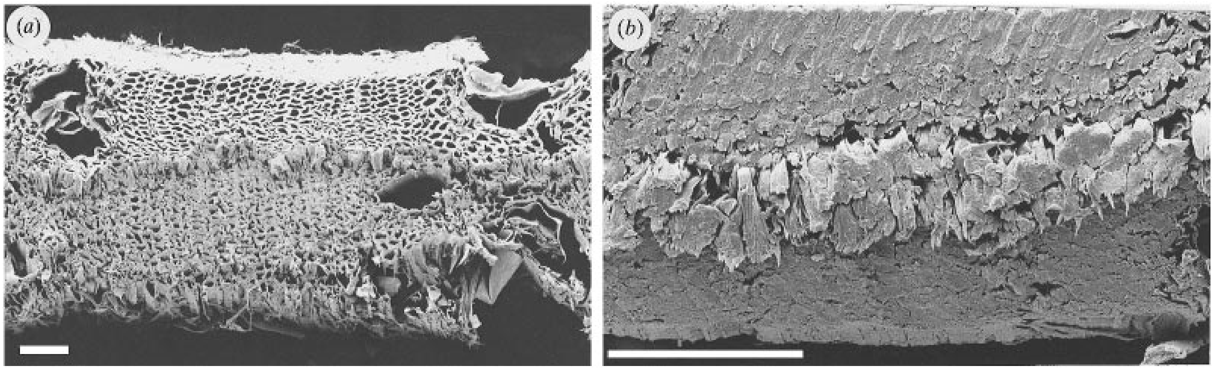

Figure 1. The appearance of the fractured surfaces of cut specimens. (*a*) LR cut in bintangor showing the distorted shape of the lumina of fibres produced by buckling (cf. the cross-section of the model fibre shown on the right-hand side of figure 9*a*). The central zone of the section is roughened, reflecting tensile fracture. The vessels, large in tropical woods, appear to have collapsed easily. (*b*) LR cut in resak showing blade marks. On either side of the roughened zone, the cut is smoother. One of the smooth surfaces lies in the same plane as the roughened region (highlighted by their similar orientation to the detector). Scale bars, 100 μm.

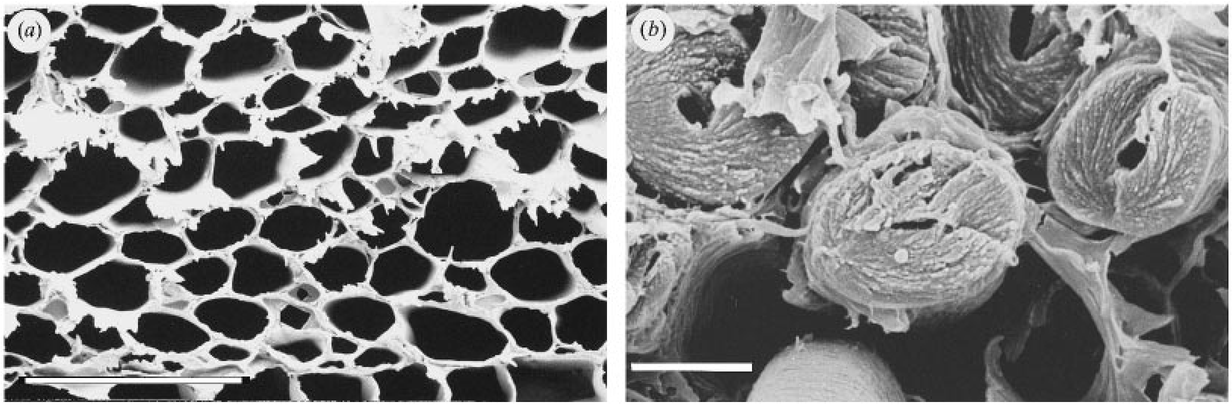

Figure 2. The appearance of the fractured surfaces of cut specimens of balsa and lignum vitae. (*a*) A macroscopic view of a balsa specimen cut in LR shows that few fibres have buckled, probably because the S2 wall layer is so thin. Scale bar, 100 μm. (*b*) A high power image of lignum vitae (*G. officinale*) fibres cut in LT. These have not really buckled either (still having roughly circular lumina) despite a thick spirally wound layer dominating the cell wall. Scale bar, 5 μm.

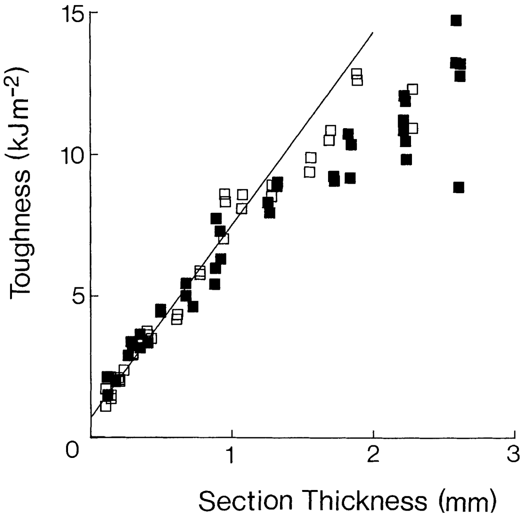

Figure 3. The relationship between toughness and section thickness for jelutong wood. Filled squares are for LT cuts, open squares are for LR. This is linear to about 1 mm thickness and then falls off (erratically due to difficulties in control of cracking even in such a light wood).

plastic work for cuts in either LT or LR directions. The slope for LT tests was steeper than those for LR, though at low relative density (< 0.25), toughness was actually slightly greater for the LR direction (figure 5*b*). No difference was observed for intrinsic toughness.

Results for LR and LT tests were then pooled. Plastic work appeared to be linearly related to relative density within the range of most commercial woods, i.e. relative densities of 0.2–0.8 (figure 6*a*). However, the lightest (balsa) and heaviest (lignum vitae) woods deviated from the trend, falling below the general regression line. This line predicts a maximum plastic work of 35.9 MJ m^{-3} at a relative density of 1.0. When logarithms were taken, the slope of the regression line was 1.26 (± 0.07), significantly different from linearity ($p < 0.01$). The derived estimate of maximum plastic work (relative density of 1.0) then rises to 42.1 MJ m^{-3}. Despite this, the estimate from linear regression is used in this paper. Whatever, lignum vitae and balsa remain outliers at 30% below values predicted at their densities. Intrinsic toughness appeared to be linearly related to relative density but there was much more

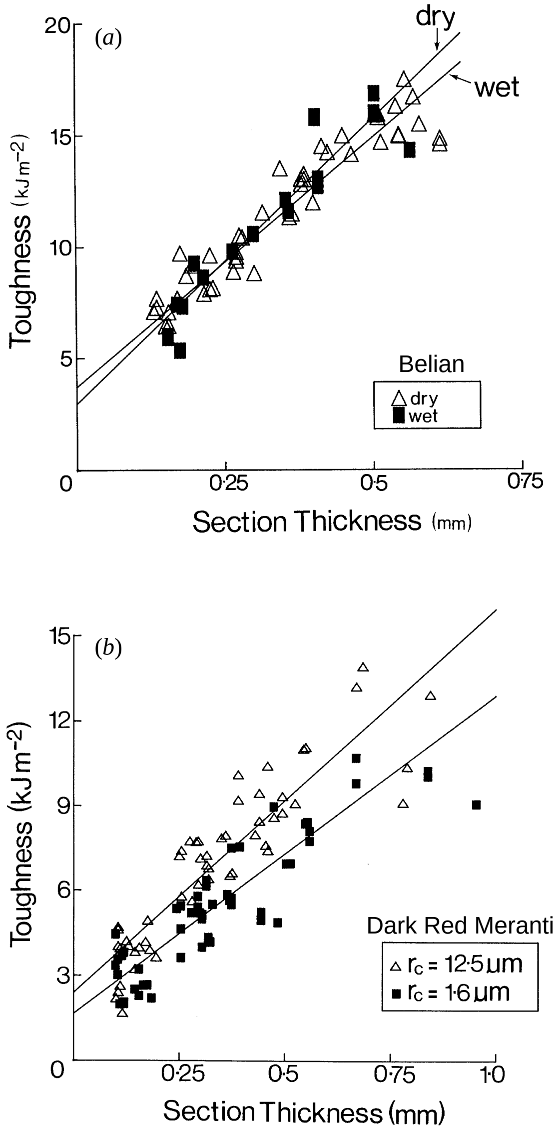

Figure 4. The relationship between toughness and section thickness. (*a*) For wet (filled squares) versus dry (open triangles) sections of belian wood; there is no difference between intercepts ($p = 0.07$) and barely between slopes ($p = 0.03$). (*b*) The influence of scissor sharpness (r_c) on the toughness of sections of dark red meranti. Use of blunt scissors (Delica Lion; open triangles) produces between a 37% (in 0.1 mm thick sections) and 15% (at 0.5 mm thickness) increase in apparent toughness compared to Dovo scissors (filled squares) over the measured range.

scatter of the results (figure 6*b*), a consequence of estimating this quantity from the intercept.

The effect of cutting wood at 45° or 10° to the grain on dark red meranti was to reduce plastic work relative to cuts at 90° (figure 7). Cuts at 45° were only marginally lower in plastic work whereas at 10°, the slope of the toughness-section thickness plot was almost zero.

Layered sections of bitis wood had much a lower toughness than intact sections (table 2). The toughness of layered values did not differ significantly ($p > 0.1$) from the intrinsic toughness of this wood, which was 2.519 (± 0.356) kJ m^{-2}, showing that a layered specimen behaved as though it had no potential for plastic work.

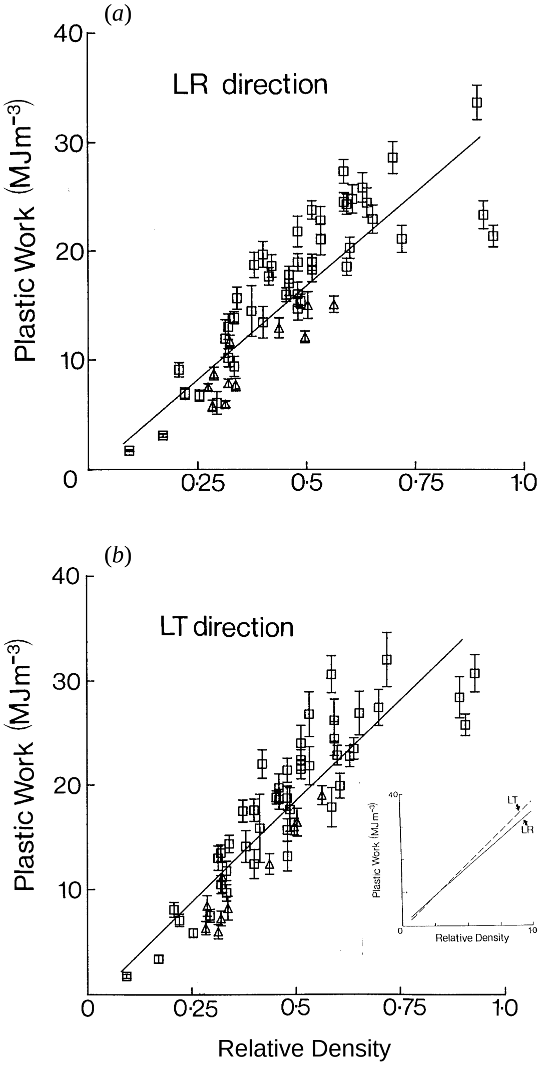

Figure 5. Linear least-squares regressions of the plastic work done in either (*a*) LR-directed cuts or (*b*) LT-directed cuts for all 56 wood samples, plotted against their relative density. The symbols are mean values; bars indicate standard errors. The inset in (*b*), with regression lines only, shows that at relative densities < 0.25, LR toughness $>$ LT and the reverse at relative densities > 0.25. Triangles represent temperate woods; squares, tropical woods.

Residuals from the plots of both plastic work and intrinsic toughness versus relative density (figure 8) were calculated. For 42 woods, the ratio of lignin to cellulose in the cell wall was significantly negatively correlated with plastic work residuals, i.e. the ratio of plastic work observed to that expected from the linear regression for its density (figure 8*a*). For 28 hardwoods, the fibre width/length ratio was also significantly negatively correlated with these residuals (figure 8*b*).

There were difficulties in obtaining accurate results for the LT direction on some of the temperate woods because the crack path lay entirely within one portion of the growth ring, ideally requiring many tests to average out variations in density. However, even given this caveat, and also that the sample of temperate hardwoods tested here was small, their work of plastic buckling, corrected for density, was about 20% lower than that of tropical hardwoods ($p < 0.002$).

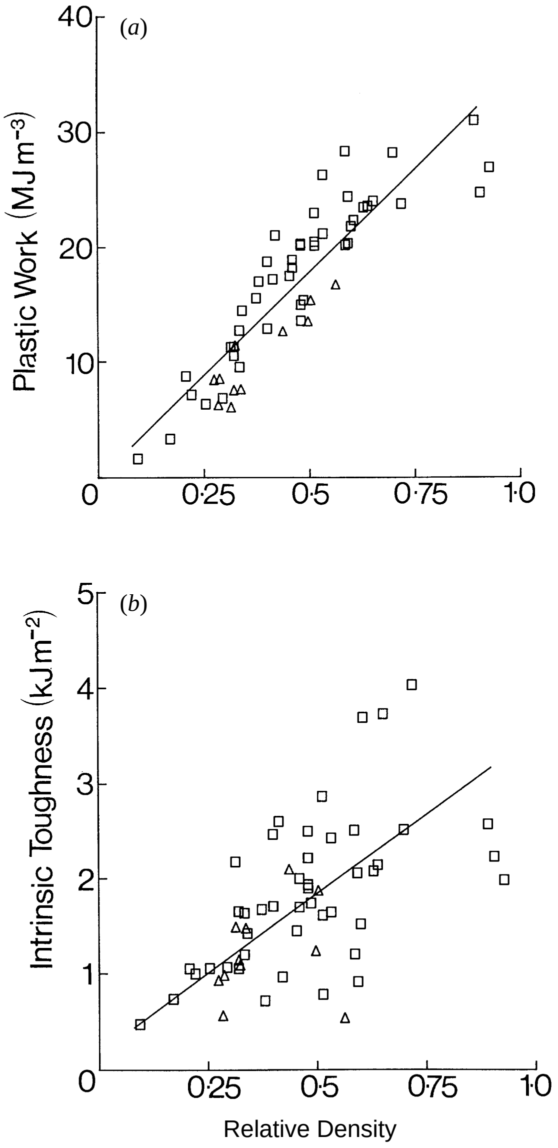

Figure 6. (*a*) The plastic work plotted against relative density. A linear regression is shown ($r^2 = 0.792$; $p < 0.0001$; plastic work = 35.9 MJ m^{-3} at a relative density of 1.0). (*b*) A similar plot for intrinsic toughness against relative density ($r^2 = 0.342$; $p < 0.0001$) for all 56 wood samples. In these plots, data for cuts in both LR and LT directions have been pooled for each wood. The scatter shown in (*b*) leads to an unreliable estimate of the intrinsic toughness of the cell wall (i.e. extrapolation of the line to a relative density of 1.0). This value was, therefore, estimated from the more extensive data shown in figure 10. Symbols as figure 5.

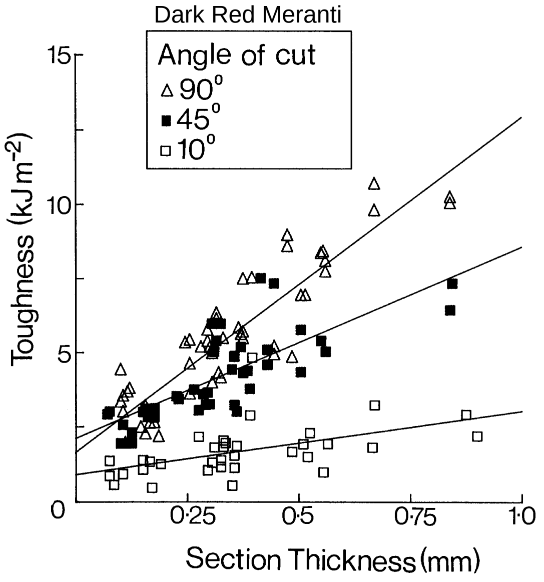

Figure 7. The effect of the angle of cut on the toughness of dark red meranti specimens; open triangles denote 90°, filled squares denote 45°, open squares denote 10°. Equal numbers of cuts in both LR and LT directions are represented.

4. DISCUSSION

In figure 9*a*, fibres or tracheids are modelled as though they are simply helically wound tubes that buckle under tension (Page *et al.* 1971). When scissors contact such tubes, they must also induce plastic buckling, both in the potential crack path (figure 9*b*) and through the thickness of the section (figure 9*c*). Most important, however, are the events involved in fracture. These seem to parallel events in guillotining (Atkins & Mai 1979, 1985), with the exception that both scissor blades are equally sharp and so indent the specimen equally. The appearance of the fractured surfaces suggests that the outer portions of the wood specimens first buckle plastically, yielding being caused by shearing across cell walls. This is followed by slow fracture (figure 9*d*). These smooth, slowly fractured surfaces lie in slightly different planes because of the wedge-like shape of the scissor blades. As the scissors continue to close, they twist the specimen and so stretch cells positioned in the middle of the specimen. This produces the fast tensile cracking seen in the central roughened zone of the fracture surface (figure 1). One of the smooth areas lies parallel to this roughened zone (figure 9*d*). Similar appearances have been found on cut surfaces of rubbery elastomers (Pereira 1995).

A body of evidence, other than visual appearance, suggests that the plastic work done on woods during scissors tests is definitely the plastic buckling of Gordon & Jeronimidis (1974, 1980). There are three requirements for the buckling mechanism to operate, each of which are consistent with our results:

(i) *Plastic buckling requires both an S2 layer to the cell wall and a cellular lumen sufficient for the wall to collapse into.* A corollary is that the mechanism should be diluted in woods of too low density to possess much S2 wall or, alternatively, be impeded by a narrow lumen in a very dense wood. This is precisely in accord with results on balsa and lignum vitae, which fall below the regression line for plastic work. Data on *Mezzettia* seed shells are even denser than any wood in this sample and, when cut across fibres, show less plastic work (25 MJ m^{-3}) than lignum vitae (Lucas *et al.* 1995).

(ii) *Plastic buckling is expressed only in intact cells.* Cells without an intact circumference cannot buckle. The results from scissoring layered thin sections, matched in thickness to single specimens, is consistent with this (table 2). The major resistance that these fragmented cells have is intrinsic toughness due to the cell wall. There may be some bending of the walls, but this seems not to be significant.

Table 2. *Comparison of the toughness of bitis wood: mean (s.d.) of tests on layered specimens versus those made from single sections*

	single sections ($n = 9$)	2–3 layers ($n = 9$)	significance (t-test)
section thickness (mm)	0.122 (0.017)	0.118 (0.037)	$p = 0.77$
toughness (kJ m^{-2})	6.169* (1.477)	3.462 (0.943)	$p = 0.0002$

n is the number of specimens.

* Significantly different from the intrinsic toughness of bitis (2.519 kJ m^{-2}) at $p < 0.001$.

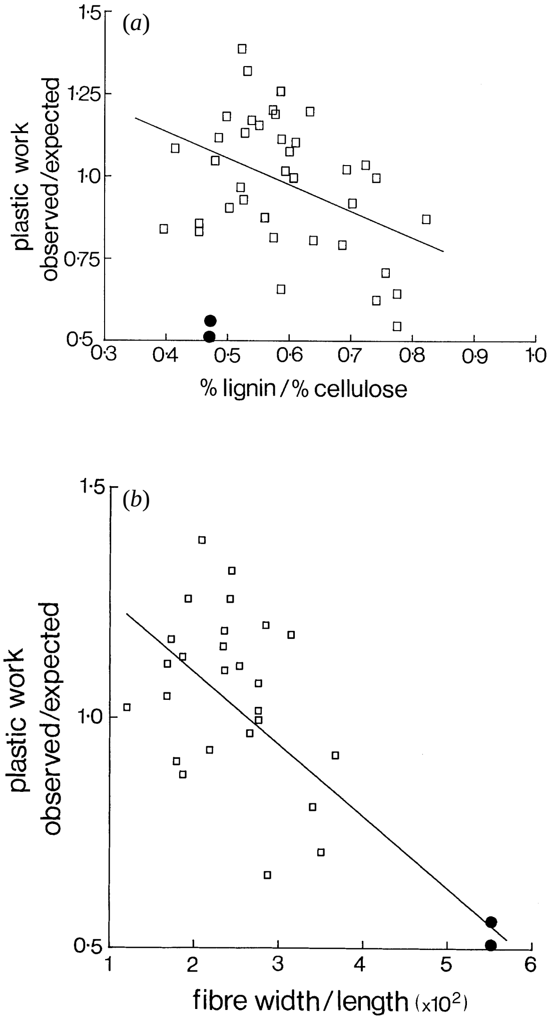

Figure 8. The effect of the chemical composition and fibre dimensions of woods on plastic work (corrected for wood density from the regression data given in figure 6*a*). Filled circles are data for balsa, which are clear outliers. (*a*) The lignin/cellulose ratio of wood (including data points for balsa: $n = 41$, $r^2 = 0.05$, $p > 0.05$; excluding balsa (as illustrated): $n = 39$, $r^2 = 0.167$, $p < 0.01$). (*b*) Fibre width/length in hardwoods (including balsa (as illustrated): $n = 28$, $r^2 = 0.55$, $p < 0.001$; excluding balsa: $n = 26$, $r^2 = 0.142$, $p < 0.05$).

(iii) *The degree of plastic buckling depends on the microfibrillar angle to the cellular axis.* Gordon & Jeronimidis (1980) made tubes that were helically wound at different angles to their long axis. This markedly altered toughness. We did not measure microfibril angle in our specimens. We did, however, change the angle of the cut to the cellular axis. Results on dark red meranti show that plastic work (the slopes shown in figure 7) probably falls as the sine of the angle of cut to the grain, being apparently totally suppressed at low angles. This is consistent with a dependence on some oriented structural element in the woods. Only the cellulosic strands in the S2 layer have a preferred orientation; they must be responsible. This result has been found before for cuts across secondary and tertiary veins of *Calophyllum inophyllum* leaves (Lucas *et al.* 1991).

Is the plastic buckling displayed in these cutting tests of the same magnitude as that seen in tensile and bending tests? The critical calculations are for the outer parts of the fracture surface, as the centre is fractured in tension. Atkins & Mai (1979) show that the plastic work done in guillotining on the outer part of a specimen depends on the shear yield stress, τ_{ys}, across cell walls, multiplied by the depth of indentation. Assuming that this applies also to scissors tests, then this can be expressed as

$$\tau_{ys} = W_p/0.33,$$

where W_p is the slope obtained from a toughness versus section thickness plot (e.g. figure 3) and 0.33 is the proportion of the fracture surface indented by one blade. The shear yield stress across cell walls is related to the tensile yield stress of wood cells

$$\sigma_y = 2\sqrt{3}\tau_{ys}/(t/l)^2,$$

where $(t/l)^2$ is essentially identical to the density of the wood (Gibson & Ashby 1988). Lastly, the size of the plastic zone of buckling

$$d_y = ER/\pi\sigma_y^2,$$

where E is the Young's modulus along the grain and R the intrinsic toughness. Only a value for E is extraneous to our data. This is, however, well known, being 35 GPa for solid cell wall in this direction (Gibson & Ashby 1988). Evaluating d_y for woods of high relative density gives $d_y \approx 0.5$ mm. This suggests two things. First, the decline seen in the slope of toughness versus section thickness curves (e.g. figure 3), approximately at a 1.0 mm thickness, may be related to the separation of two 0.5 mm plastic zones, each induced by one of the scissor blades. If cracks could be controlled properly at thicknesses > 1.0 mm in cutting tests, then toughness should rapidly plateau off to a maximum value at this thickness. Second, a coincidence between this plateau and the length of fibres in hardwoods, also of the order of 1.0 mm (Peh *et al.* 1986), suggests that all cells in the potential fracture path may buckle along their entire length during cutting. This is also supported by the dependence of plastic work on fibre dimensions (figure 8*b*). This

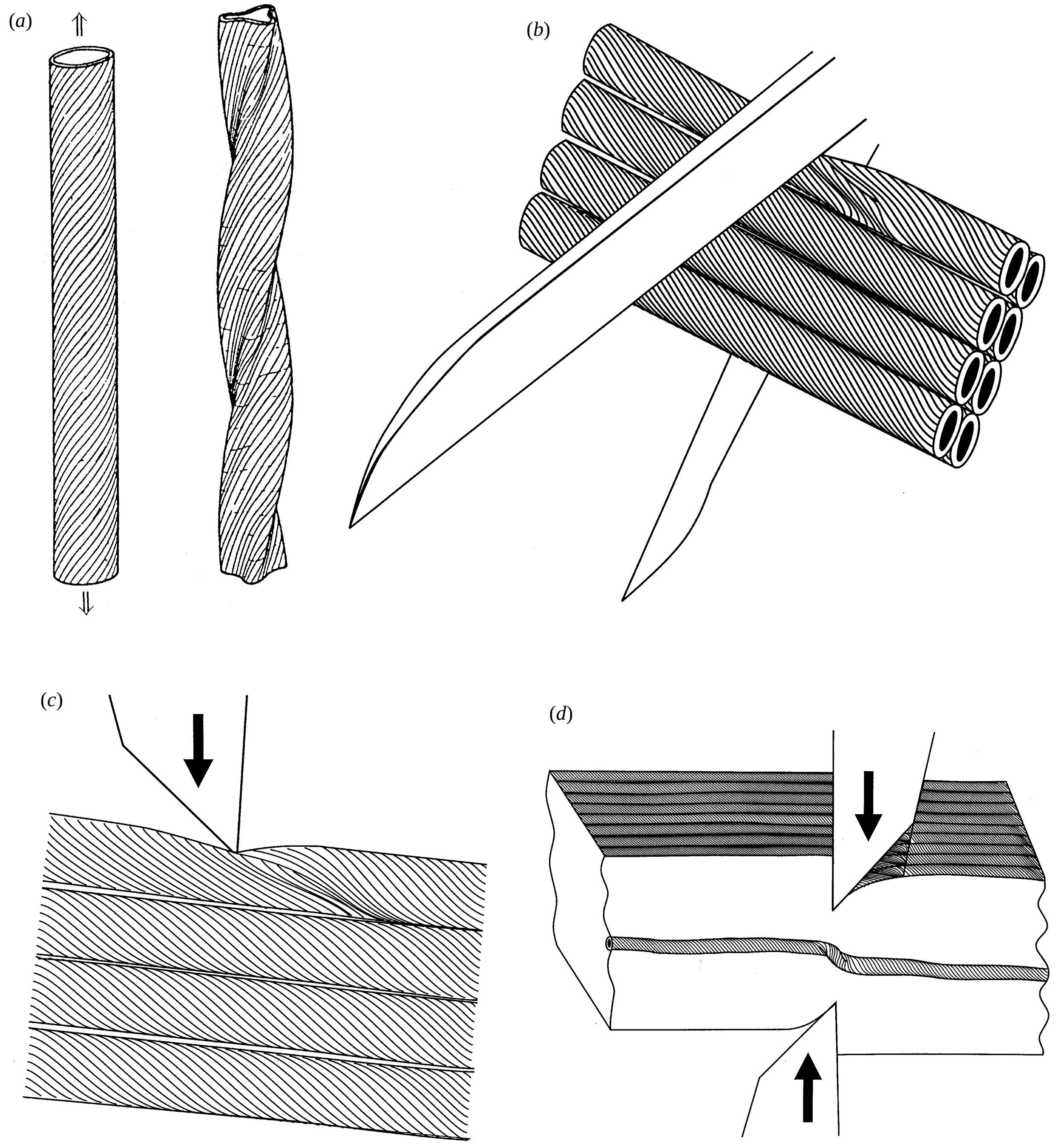

Figure 9. Events during cutting. (*a*) Wood cells (fibres or tracheids) are modelled as helically wound tubes (left) which buckle under applied tensile stress (right). The cells also buckle (*b*) in front of a scissor blade and (*c*) through the thickness of the section to be cut. In (*d*) the section is now fractured and twisting off. The outer thirds of the section are being indented by the blades which are shearing them across cell walls, producing buckling (not shown). The middle of the section is under tension. A cell such as that shown in the centre of the section will buckle and then fail in tension. (Figure 9*a* is redrawn from Page *et al.* (1971). Reprinted with permission from *Nature*. Copyright (1971) Macmillan Magazines Ltd.)

would not be anticipated if the region of buckling was small compared to fibre dimensions because fibre size would not then matter. Fibre dimensions may well be optimized for maximum work of buckling.

Results from cutting tests seem likely, from the above, to be comparable to those from other tests. To be sure, we used the slope in figure 6*a* relating plastic work to relative density to calculate a normalizing factor for all woods of commercial importance (relative densities 0.2–0.8). If we assume plastic work in any of these woods to peak at a 1.0 mm specimen thickness, then the contribution of plastic work in a hypothetical solid wood (i.e. of relative density 1.0) is this slope, 35.9 MJ m^{-3}, multiplied by 1.0 mm. This gives 35.9 kJ m^{-2}.

We also need to obtain a value for the contribution from the cell wall itself to toughening the wood. The plot for the intrinsic toughness of woods versus relative density shows a lot of scatter (figure 5*b*). However, placing woods in the context of data for 19 other plant tissues or plant-based materials, obtained by identical methods (Lucas *et al.* 1995), shows woods to lie close to

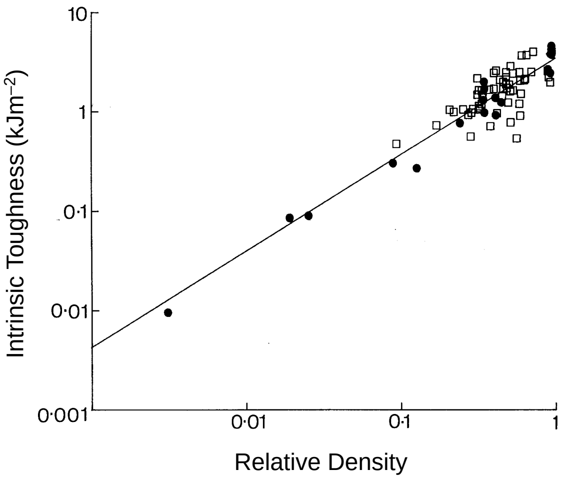

Figure 10. The relationship between the intrinsic toughness of the cell wall and relative density for the woods (open squares) measured in this study together with data for 19 other plant tissues or plant-based materials (filled circles), from Lucas *et al.* (1995). Logarithmic axes are used because of the great spread of data ($r^2 = 0.844$; $p < 0.0001$). The slope is 0.967 (± 0.048), which is not significantly different from 1.0. The intrinsic toughness at a relative density of 1.0 is 3.454 kJ m^{-2}. Table 1.

Table 4. *Prediction of results of 'work area' tests from the overall toughness of wood tissue (see text)*

wood	density (kg m^{-3})	work of fracture (kJ m^{-2}) (from Jeronimidis 1980)	predicted toughness (kJ m^{-2})
balsa	225	5.6	5.9
sitka spruce	600	24.0	15.7
teak	825	22.0	21.6

the general regression line (figure 10). The predicted cell wall toughness, at a relative density of 1.0, is 3.45 kJ m^{-2}. This is well above values for brittle materials, which generally have a toughness < 0.2 kJ m^{-2}. Cell walls must be toughened by mechanisms such as delamination, microfibrillar pull-out and bridging of cracks by matrix ligaments (which we have photographed). Despite these mechanisms, for any given commercial wood, the cell wall clearly provides only about 10% of the work arising from plastic buckling. This is very strong support for the contention that the latter does indeed explain the basis for woody toughness (Gordon & Jeronimidis 1974, 1980).

The best results (in terms of sample size) from K_{IC} tests on woods reported by Ashby *et al.* (1985) are shown in table 3. For this purpose, Ashby *et al.*'s results are converted to energetic values simply by dividing K_{IC}^2 by E because such fracture tests are thought to exclude plastic work. (The matrix of elastic constants which is strictly necessary to do this for orthotropic materials has been ignored here. They are not known for many woods; however, in those where they are known, they do little to modify our conclusions.) The right-hand column in table 3 gives the toughness predicted from the intrinsic toughness of the cell wall (3.45 kJ m^{-2}). Our predictions are remarkably good, particularly for results from notched tensile tests. Ashby *et al.* (1985) hypothesize that K_{IC} values are important in predicting whether cracks deflect along the grain at the edges of cells rather than cross the wall. We interpret this to mean that plastic buckling is not important in determining crack direction.

Summing the work contributions of plastic buckling and cell wall gives what we term an overall toughness for wood tissue. This is 39.35 kJ m^{-2}. No wood could actually attain this toughness because buckling requires a lumen. However, it provides the normalizing factor required to compare results of scissoring most woods with those from work area tests. In table 4 such results are given by Jeronimidis (1980) for a large number of tests for three woods. Again, the right-hand column of the table gives our predictions, this time derived from overall toughness. These are very accurate for the two tropical woods—balsa (fairly dense specimens) and teak—but a significant underestimate for spruce.

The evolution of hardwood anatomy into separable mechanical elements (fibres) and hydraulic conduits (vessels) from the tracheids of softwoods is not currently thought to involve any mechanical penalty (Tyree *et al.* 1994). However, vessels in this study appeared to collapse easily and may be detrimental to toughness. Tropical hardwoods contain a small number of highly efficient large vessels. In contrast, temperate hardwoods contain a large quantity of small vessels (Baas 1986), probably to spread the risk of vessels becoming occluded by developing freeze-induced embolisms in cold winters (Tyree *et al.* 1994). The increased area given over to vessels in temperate hardwoods may be responsible for their much lower toughness compared

Table 3. *Prediction of results of K_{IC} tests (converted to energetic values) from intrinsic toughness*

wood	density (kg m^{-3})	measured* toughness (kJ m^{-2}) (from Ashby *et al.* 1985)	predicted toughness (kJ m^{-2})
ash	674–676	1.825–1.844	1.550
balsa	98–101	0.089–0.165	0.230
beech	624–670	1.340–2.454	1.435–1.541
pine	507–572	1.095–2.188	1.166–1.316
teak	639–725	0.787–1.711	1.470–1.668

* The low end of the range given is generally for results from tensile tests, the high end for three-point bending.

to tropical hardwoods. This seems more likely than any general differences between them in microfibril angle, which can vary with growth season in some temperate woods (Cave 1969).

The manner of bonding of microfibrils to the chassis of the cell wall is probably important in setting the work of plastic buckling. If microfibrils are bonded firmly all along their length, then this will suppress toughness (Atkins 1974). This may explain why the ratio of lignin to cellulose (and not the quantity of lignin alone) in the cell wall is negatively correlated with the propensity to plastic work (figure 8*a*). Lignification proceeds from the margins of the cell. If it impregnates the S2 layer and crosslinks the cellulose too tightly, then plastic buckling may be suppressed. The pay-off might be greater strength but lower toughness. However, the explanation of why woods differ in these ways must obviously be sought in the habitat of the tree species concerned.

The differences between plastic buckling in the LT and LR direction seem to be explained by the direction of the rays in woods. These tissues, which have a transport function, run radially and so cuts in the LR direction run along their length whereas cuts in the LT cross them. On average, more ray tissue would be cut in LR tests than in LT tests. In low-density hardwoods, thin-walled rays may actually be denser than fibres (Easterling *et al*. 1982; Gibson & Ashby 1988); thus, the LR direction is tougher than LT in these woods. However, above relative densities of 0.25, hardwoods have increasing thicker-walled fibres without a corresponding increase in the density of ray tissue. The latter remain relatively thin-walled. The toughness relationship, therefore, becomes reversed in these denser woods, with LT cuts costing more than those directed in LR.

In summary, a large amount of information on the toughness of woods can be obtained from very simple tests on very small specimens (much smaller than those used in small-scale tests reported previously; Sexton *et al*. 1993) that direct the crack very effectively. These tests can be made on a portable tester and there exist very simple methods of fashioning specimens (e.g. with a wood plane or pencil sharpener). The effect of silica in some woods (e.g. teak, keruing and bitis in this study) may be to damage scissor blades. This can be dealt with pragmatically by inspecting, changing or resharpening scissors regularly. Even so, the effect of extreme variation in blade sharpness on the results is not alarming; a 7.81-fold increase in the radius of curvature of blade edges increases plastic work by only 15–37%.

The thickness of the S2 wall layer is variable, but it is commonly about half the total wall thickness. We therefore predict that the specific contribution of this wall layer to the toughness of wood is about 0.07 MJ m^{-2} (somewhat less than the ideal value; Gordon & Jeronimidis (1980)). The use of this for predicting wood toughness is, however, limited by the effect of variation in mean microfibril angle. We think that this variation should be explored preferentially in tropical woods, because there are fewer complications with growth rings.

The amount of practical work required to calculate toughness from cutting can be reduced substantially from that reported here. The toughness of wood is probably obtainable from two sections, each conveniently about 0.5 mm in thickness. The intrinsic toughness could probably be best estimated by cuts at about 5° to the grain, because such cuts appear to suppress plastic buckling (figure 7). The work of plastic buckling can be obtained from the other section by conventional cuts at 90° to the grain, scaled up to that of a 1+ mm thick section using the normalizing values quoted here. All that would be needed to obtain such sections would be to plane a small core of heartwood in the appropriate direction.

The tests may also come in useful for assessing the onset of fungal decay in wood, as toughness is particularly sensitive to this: differences in the cell wall substances attacked by brown-rot versus white-rot fungi could provide valuable information on the roles of these substances in toughening the cell wall (Sexton *et al*. 1993). However, part of the value of this study lies outside wood alone. Woody tissue in any plant material should behave very similarly. There is some evidence for this from the behaviour of veins (probably the fibres) in *Calophyllum inophyllum* leaves (Lucas *et al*. 1991) and also from seed shells (Lucas *et al*. 1995). In particular, seed shells are worth exploring in considerable detail because they are more homogeneous than wood in cell type and vary a great deal in the lay-up of fibres. Furthermore, seed shells have no transport function and can have much higher densities than woods, enabling predictions about the potential for the toughening mechanism to be tested more fully. The development of woody toughness in ripening seeds, pods and maturing leaves has value in studies of mammalian feeding behaviour because toughness may form one of the principal methods of detecting high fibre (Choong *et al*. 1992; Hill & Lucas 1996). Experiments that dissociate the cost of cell wall fracture from woody toughness show exactly why fibre content is not proportional to toughness. It is not just the amount of cell wall that is present that sets toughness levels, it is its organization. It would be a mistake to calculate the resistance of any plant tissue to fracture by performing K_{IC} tests, followed by the application of the formula $R = K_{IC}^2/E$. This would establish the cell wall or fibre-based toughness, but not whether there was any plastic buckling, which, we have shown, typifies woody tissue. Hypothetically, if the cell wall of any given tissue, in a block more than 1 mm thick, could reorganize from a wall in which microfibrils in different lamellae were randomly directed to one in which they were all identically oriented, then the overall toughness of that tissue would jump ten-fold.

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