JOURNAL OF MATERIALS SCIENCE 26 (1991) 1947–1950

Strength and fracture of grasses

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The strength of leaves from six grasses of sclerenchyma content from 2% to 30% has been measured. The strength of sclerenchyma is 144 MPa. As long as the sclerenchyma fibres are mechanically separated laterally, they toughen the leaf by reducing its sensitivity to damage. At high sclerenchyma contents the fibres tend to be laterally joined and the leaf, although stronger, becomes more brittle.

1. Introduction

The fracture properties of plants are of interest both to biologists and to engineers [1, 2]. Botanists (including those concerned with horticulture and agriculture) frequently need to know how readily the plant resists (or encourages) fracture, for understanding resistance to various physical stimuli or the mechanisms of dehiscence or abscission. Zoologists and agriculturalists are concerned with the ease with which animals can gather food and reduce it to digestible form [3]. The engineer is interested in the generality of his ideas and models, especially when applied to complex biological structures. Grasses provide an ideal medium for developing this approach because their leaves are essentially linear in design. It is then relatively easy to apply simple mechanical models derived from studies on composite materials and to derive information of direct biological importance.

It has already been established that the sclerenchyma is the main load-bearing component and its presence as isolated bundles makes grass leaves difficult to break [4, 5]. The present study shows this to be true of a wide range of grasses, but that large amounts of sclerenchyma (as found in many "hard" tropical grasses) actually make the grass more brittle because the bundles fuse laterally.

2. Materials and methods

Leaves of grasses of several species (*Poa pratensis*, *Holcus lanatus*, *Bromis hordescens*, *Deschampsia caespitosa*, *Dactylis glomerata*) were collected from Reading University campus park in late May. *Stipa gigantea* came from the gardens of the Department of Botany. Sections were cut by hand and examined, unstained, by light microscopy. Sclerenchyma fibres were identified more readily by their higher birefringence shown in the polarizing microscope. From these sections the amount of sclerenchyma and vascular material were measured as the percentage of the cross-section which they occupied. The leaves were tested mechanically in tension in an Instron 4202 bench-top test machine. Many of the test leaves had short notches, running across the leaves, cut in them halfway along their length before testing to allow their fracture properties to be measured [4, 5]. Notches were cut centrally or in the two edges. The length of the notch, a, was divided by the width of the leaf, W, to give a relative notch length a/W, varying between 0 and 1.0. From the results of these tests a stress concentration factor, K_{IC}, was calculated, hence a work to fracture, W_{f} [4]. Some sclerenchyma fibres were also dissected from the leaves and tested in tension.

3. Results

The main results are shown in Table I. The proportion of fibre (i.e. sclerenchyma tissue) in the different grasses varies by more than an order of magnitude, but the properties of the fibres, as shown by analysis of variance, seem to be more or less consistent. The proportion of vascular tissue is much more constant. The notch test graphs (Fig. 1a–e) tend to be very similar. In general they give a straight-line relationship of moderate correlation for edge notches or a more or less concave-downwards curve for centre notches. This shows that the leaves are generally insensitive to notches or other damage, but that the site of the damage can have some influence. However, *S. gigantea* leaves are significantly notch-sensitive (Fig. 1f). In section all the leaves except that of *S. gigantea* have the sclerenchyma tissue in discrete bundles: *D. caespitosa* has thickened epidermal cells in addition; the leaves of *S. gigantea* contain not only such thickened epidermal cells but also large areas of sclerenchyma which are continuous across the leaf (Fig. 2). The fracture path across the blade is straight in the grasses with isolated fibres, but in *S. gigantea* it is very jagged, looking very much like the fracture path seen in dried grass [5]. With all the grasses there is a tendency for notches in the centre of the leaf to be apparently more embrittling than notches in the edge of the leaf, since the strength–(a/W) curves for such specimens are somewhat concave downwards. A similar result was reported previously [4]. This is probably because the fibres towards the centre of the leaf, and especially those in the midrib, tend to be larger, so cutting them

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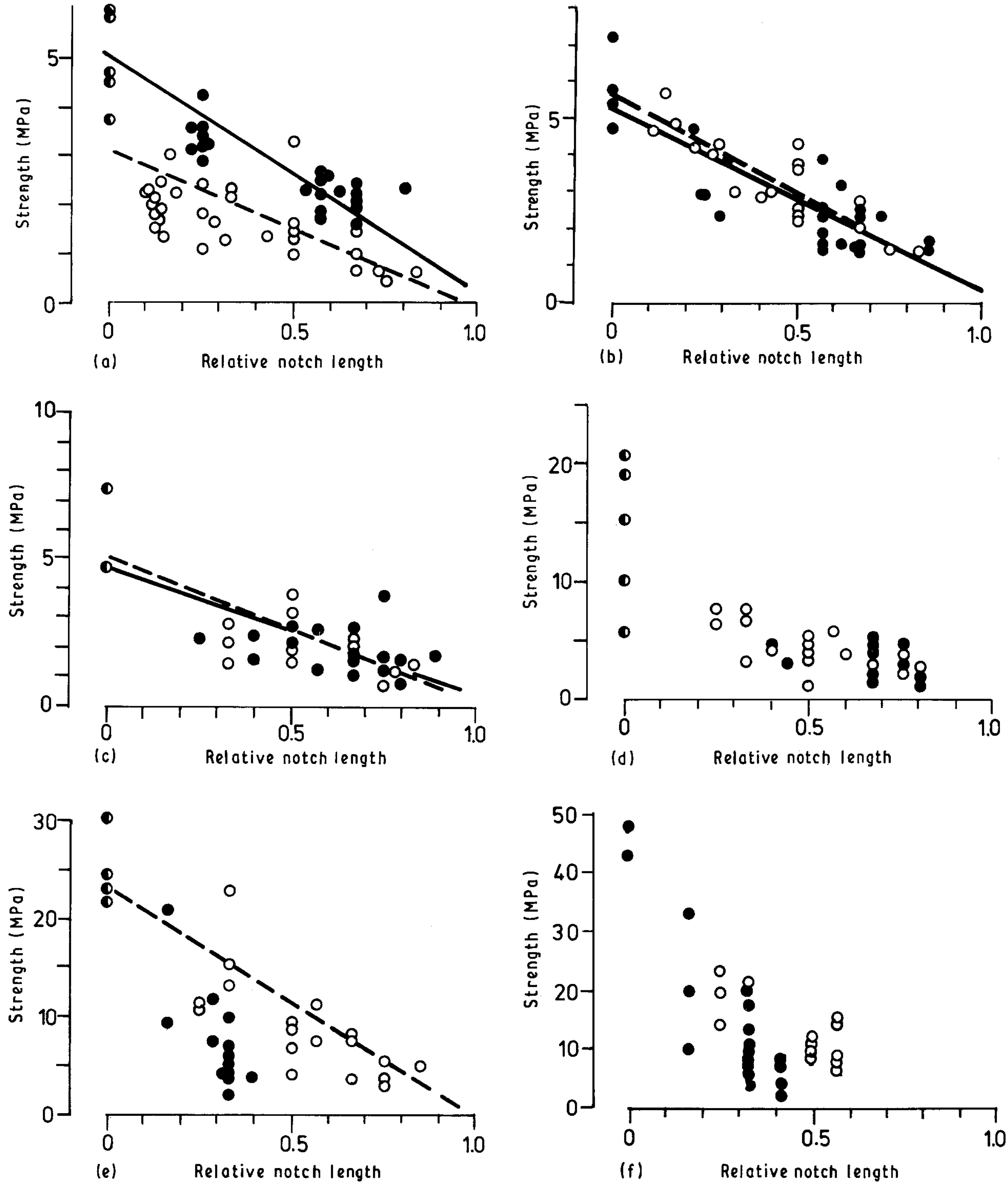

Figure 1 Notch sensitivity of leaves of various grasses. (●, —) Edge notches, (○, ---) centre notch, (◐) no notches. (a) *Holcus lanatus*, (b) *Dactylis glomerata*, (c) *Poa pratensis*, (d) *Bromis hordescens*, (e) *Deschampsia caespitosa*, (f) *Stipa gigantea*. The lines drawn are calculated from regression analysis, but are drawn only where a straight line will cut the horizontal axis at a/W greater than 0.9. Lines to fit the remaining sets of data would have to be curved (concave downwards) to meet this criterion, and so presumably indicate notch-sensitivity.

has a greater effect on strength than cutting those at the edge. The strength of the leaves is closely related to the amount of sclerenchyma present (Fig. 3). The stress intensity factor and work of fracture are fairly constant at a sclerenchyma volume fraction of less than 10% (Table II), and increase markedly with increasing sclerenchyma content.

4. Discussion

In general these results support and amplify previous work [2, 4, 5] which showed that grass leaves may be modelled mechanically using a simple Voigt model. The basic predictions of this model are that the stiffness and strength of the leaves are linearly related to the amount of sclerenchyma and that so long as the fibres are separated by relatively weak parenchyma cells the material will be insensitive to damage. Both these findings are supported by the present study, which shows that the fibres from a range of grasses have practically identical mechanical properties (Table I and Fig. 3). As a corollary to the mechanism by which grasses with less than 10% of sclerenchyma

TABLE I Summary of mechanical and morphological measurements on grass leaves. Variation quoted is the standard deviation; numbers in brackets are sample size

	Holcus	*Dactylis*	*Poa*	*Bromis*	*Deschampsia*	*Stipa*
1. Volume fractions						
Sclerenchyma	0.022	0.024	0.06	0.09	0.147	0.313
Vascular system	0.084	0.044	0.043	0.032	0.097	0.126
2. Stiffness of fibres (GPa)						
mean (± S.D.)	3.024 (± 1.91)	7.36 (± 7.18)	–	7.47 (± 3.60)	3.62 (± 2.15)	2.05 (± 0.95)
No. of determinations	(7)	(8)		(9)	(7)	(6)
3. Ultimate strain of fibres						
mean (± S.D.)	1.628 (± 0.596)	1.487 (± 0.901)	–	1.60 (± 0.597)	1.834 (± 0.915)	1.19 (± 0.560)
No. of determinations	(9)	(8)		(9)	(6)	(8)
4. Strength of leaf (MPa)						
mean (± S.D.)	4.98 (± 0.886)	5.84 (± 1.06)	6.07 (± 1.88)	14.18 (± 6.277)	24.83 (± 38.44)	45.88 (± 32.39)
No. of determinations	(10)	(4)	(2)	(5)	(4)	(2)

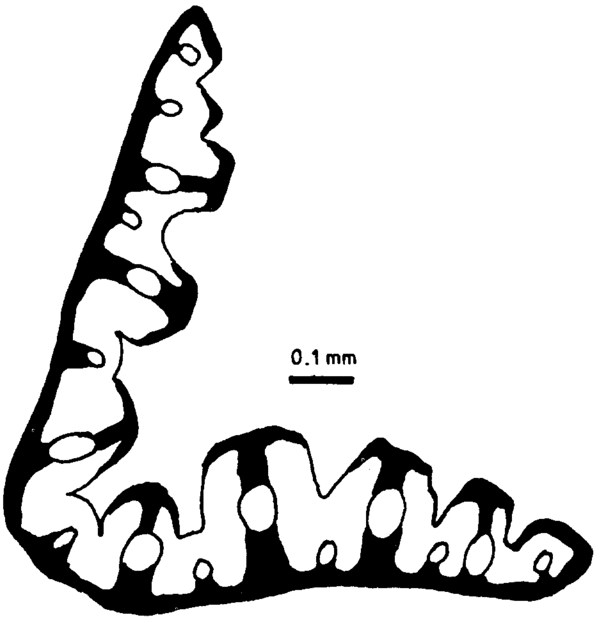

Figure 2 Section of leaf of *Stipa gigantea*. Sclerenchyma shown black, vascular bundles indicated as ovals.

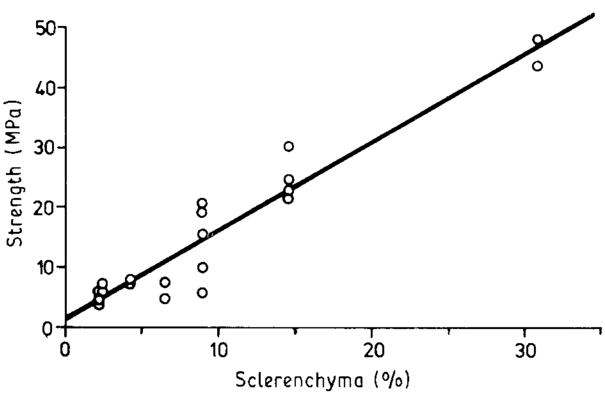

Figure 3 Correlation between strength of grass leaves and percentage of sclerenchyma in the cross-sectional area. Regression formula: $y = 1.444x + 1.525$, regression coefficient = 0.962.

TABLE II Values of stress intensity factor (K_{IC}) and work to fracture (W_f) of grasses calculated from data shown in Fig. 1

	Edge notch		Middle notch	
	K_{IC} ($MN\,m^{-3/2}$)	W_f ($kJ\,m^{-2}$)	K_{IC} ($MN\,m^{-3/2}$)	W_f ($kJ\,m^{-2}$)
Holcus	2.35	1.66	1.61	0.78
Dactylis	–	–	3.02	1.13
Poa	1.75	0.85	1.95	1.06
Bromis	4.13	2.08	3.91	1.87
Deschampsia	4.38	4.83	8.80	19.44
Stipa	6.985	21.65	11.03	53.97

resist damage, the data from *S. gigantea* and *D. caespitosa* show that if the sclerenchyma bundles are interspersed with material of similar mechanical properties, the leaf becomes brittle and more susceptible to accidental damage, even if it is stronger in simple tension. This must be due to the increased shear stiffness of the sclerenchyma giving suitable conditions for the concentration of stresses at the tip of the notch. The similarity of the fracture surface of the broken leaf of *S. gigantea* to the fracture surface of dried grass supports this interpretation [5], as does the higher stress intensity factor (Table II). The apparent anomaly that the grass with the highest work of fracture is also the most notch-sensitive brings into question the appropriateness of using K_{IC} in the analysis of such a highly anisotropic material. In short it is probably not correct to use it in such circumstances and some other, probably more pragmatic, method should be substituted [1, 6]. It may well be appropriate for *Stipa*, however, with its continuous sclerenchyma layer across the leaf. Greenberg *et al.* [2] maintain that the epidermal cells also make an important contribution to the tensile mechanical properties of grass leaves, although they did not test any leaf components in isolation. The epidermal cells certainly tend to have thicker walls on the outside surface, a characteristic which is variable between species and seems to be responsible for the slight notch-sensitivity of *D. caespitosa.* However, I have no evidence that the epidermis contributes more than a few per cent to the tensile stiffness or strength of these leaves.

The strength of sclerenchyma, calculated from the regression coefficient of the line in Fig. 3, is 144 MPa, which can be compared with a maximum value for strength of only 112 MPa from measurements on individual fibres. The reason for this discrepancy is probably damage sustained by the fibres whilst being dissected for testing. The individual fibres will be as sensitive to damage as the leaves of *S. gigantea*, and for the same reasons. The estimates of cross-sectional area used for these calculations take no account of the hole down the middle of the fibres: if this is done, then the estimates of stiffness and strength will increase by about five-fold, giving figures for the cell walls of stiffness about 25 GPa and strength about 0.7 GPa. This is still somewhat lower than the normally quoted stiffness of cellulose (80 GPa).

5. Acknowledgements

The author thanks Mrs Tracy Brazier and Miss Viv Lancaster for performing the bulk of the experimental work reported here.

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Received 21 December 1989
and accepted 16 May 1990