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The mechanical design of grass

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Grass can be modelled satisfactorily as an orientated fibrous composite. The fibres account for 90 to 95 % of the longitudinal stiffness. The grass leaf shows little or no notch sensitivity together with a specific work-of-fracture of approximately 30 Jm^{-2}. This probably affects the way in which animals gather grass when they feed on it.

1. Introduction

The mechanical properties and analysis of grass are of interest for several reasons. Agronomists want to know if mechanical factors affect the choice of grass by grazing animals; whether mechanical properties are concerned in the resistance of grass to trampling; how mechanical properties affect the digestibility of grass; and how they affect processing (harvesting, hay–making etc.). Naturally this information is of use to the plant breeder who can then select for the important characteristics. Grass is also of interest for its mechanical design. It is probably the simplest of all plants from the mechanical point of view. In this paper it is shown that grass can be adequately described by simple composite theory, at least to a first approximation.

2. Materials and methods

Leaves of perennial rye-grass, *Lolium perenne*, L., grown under controlled environmental conditions, were provided by Dr P. J. Harris, Grassland Research Institute, Hurley. The leaves were chosen to be uniform in age and development. They were stored at 4° C for no more than 24 h after harvesting and were immersed in distilled water for at least 0.5 h before use to bring all the cells in the grass to a consistent osmotic state. Samples, chosen for their constant width, were cut from the leaves immediately before use. All samples were tested wet. The tensile tests were performed on a table model Instron testing machine at a cross-head speed of 50 $\mathrm{mm\,min}^{-1}$. The same equipment was used for the fracture tests; the notches (of length, a) were made with a razor blade and measured with a travelling microscope. The width, W, and thickness of the leaves were measured with vernier calipers. The cross-section of grass being uneven (see Fig. 1) this method overestimated the true cross-sectional area by about 25 %. This was allowed for in the Voigt model and in other estimates of stress. The dynamic stiffness was estimated using the grass leaf as a freely vibrating cantilever. A narrow slit of light was projected onto a sheet of photographic paper wrapped around a drum. The grass leaf was placed across this beam as close to the drum as possible and set vibrating by flicking it. The drum was rotated and a trace obtained on the photographic paper which was then developed.

2.1. The anatomy of the grass leaf

In section the leaf appears as in Fig. 1. The main fibrous tissue is the sclerenchyma, most of which occurs in distinct bundles of fibres, but some of which occurs in association with the bundles of vascular tissue which transport water and nutrients along the leaf. One surface is ridged, the other smooth. Parts of the leaf were dissected out under a binocular microscope. This was easily undertaken for the fibrous tissue but not for the cuticle, so fewer samples of the latter were tested. In plan view the grass leaf is parallel-sided for most of its length with all the morphological elements running parallel to each other; however, the leaf tapers towards the end and this part was not used in the mechanical tests. Estimates of the volume-fraction, V_f, of vascular bundles and sclerenchyma fibres were made from tracings of a leaf section, cutting out the tracing paper and weighing it. This has been shown to be the best method [1] and the results obtained in this work agreed with those of other authors [1].

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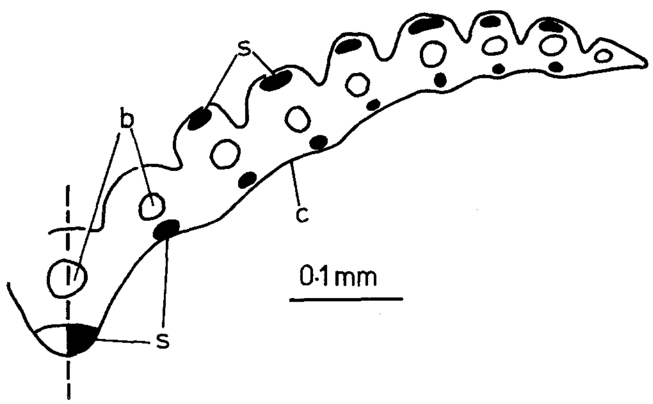

Figure 1 Transverse section of *Lolium perenne* leaf showing sclerenchyma fibres (s), vascular bundles (b), cuticle (c). The remainder is composed of relatively large thin-walled cells under turgor pressure which are considered in this paper as forming a homogeneous "matrix" phase.

3. Results

3.1. The simple composite model

Table I shows measured values for whole grass leaf and for some of its components. Most of the transverse stiffness can be accounted for by the cuticle covering the leaf: tests on this component alone gave forces of similar magnitude to those for the whole leaf. However, assuming this transverse stiffness can be regarded as the stiffness of the non-fibrous components and that this is isotropic (i.e., regarding the transverse modulus as equivalent to a matrix modulus) the Voigt model can be applied to give the overall modulus as:

$$E_c = (E\,V_f)_1 + (E\,V_f)_2 + (E\,V_f)_3 \ldots \quad (1)$$

Applying this model to grass gives,

$$E_L = E_T + (E\,V_f)_{\text{bundles}} + (E\,V_f)_{\text{fibres}} = 10.07 \times 10^8\ \text{N m}^{-2},$$

where E_L is the longitudinal modulus, E_T is the transverse modulus of the leaf. This is twice the value for E_L found by experiment (Table I) and this could be accounted for if the fibres had been measured as 0.02 mm instead of 0.03 mm in diameter. At any event, the fibres account for between 90 and 95 % of the longitudinal stiffness of the leaf.

3.2. Fracture toughness

The fracture properties of the grass were investigated using the simple notch fracture test, several different positions being used for the notch. Except with very small notch lengths the specimen always broke at the notch. Figs 2 and 3 show results from tests using single edge notches on whole or half leaves (see Fig. 2) and symmetrical notching (single centre or two equal edge-notches) on whole leaves (Fig. 3). The half-leaves were prepared by slicing the leaf with a razor to one side of the mid-rib and using the piece without the mid-rib. Obviously single edge notches produce much more scatter in the results and in these specimens the crack was often deflected along

TABLE I Stiffness and volume-fractions used in the Voigt model

Sample	Modulus (N m^{-2})	Standard deviation	Sample size
Tensile tests			
Longitudinal modulus			
Leaf (E_L)	5.54×10^8	0.745×10^8	40
Fibres	2.26×10^{10}	0.928×10^{10}	7
Bundles	8.38×10^8	4.63×10^8	5
Transverse modulus			
Leaf (E_T)	1.408×10^7	0.405×10^7	46
Dynamic test			
Longitudinal modulus			
E_{dynamic}	4.438×10^7	1.828×10^7	10
Volume fractions		Bundles: 4.12% fibres: 4.24%	

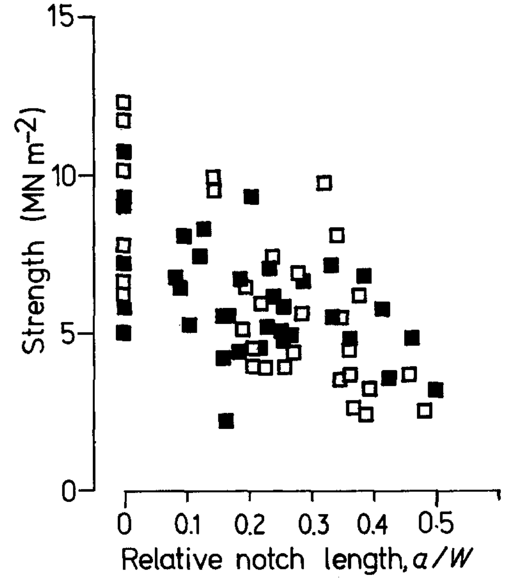

Figure 2 Results of edge-notch fracture tests showing fracture stress against notch length, a, as a fraction of the width of the leaf W: ■, whole leaf; □, half leaf. Values for whole leaf from Fig. 3 are included for zero notch length.

the fibres, occasionally until the leaf split longitudinally. The symmetrically notched specimens broke much more cleanly and Fig. 3 suggests that grass is more or less insensitive to edge defects, which therefore do not make the grass more liable to fracture through stress-concentrating effects. This appears to be more true for grass leaves which have the mid-rib intact: the solid line in Fig. 3 is the calculated regression line for results from such leaves and has a respectable correlation coefficient ($r = 0.839$). The dotted line (back-calculated from Fig. 4) suggests that if the mid-rib is cut, the leaf becomes more sensitive to defects. To investigate this further the stress-intensity factor and specific work of fracture were estimated for the two sets of data.

The stress intensity factor, K, is given by

$$K = \sigma(\pi a)^{1/2} F(a/W), \tag{2}$$

where

$$F(a/W) = \frac{1.122 - 0.561(a/W) - 0.015(a/W)^2 + 0.091(a/W)^3}{[1-(a/W)]^{1/2}} \tag{3}$$

for a double edge-notched specimen, or

$$F(a/W) = \frac{1 - 0.5(a/W) + 0.326(a/W)^2}{[1-(a/W)]^{1/2}}$$

for a centre-notched specimen [2] and σ is the applied stress. These formulae estimate $F(a/W)$ to better than 2% [2]. Fig. 4 shows the square of the fracture strength, σ^2, plotted against $[aF^2(a/W)]^{-1}$, which gives a line whose slope is $K_c^2\pi$, where K_c is the critical stress intensity factor for cracking.

Table II shows relevant values for the regression lines shown and also give estimates of the specific work-of-fracture, R, estimated from the relationship

$$R = \frac{K^2(1-\nu^2)}{E}. \tag{4}$$

The Poisson ratio, ν, has not been measured for grass stretched longitudinally and it is doubtful whether an accurate estimate could be made since the leaf tends to curl transversely as it is being extended. Accordingly estimates are given of R for two values of ν, 0.3 (which is probably the more correct) and 0.5 (which is the commonly, and usually erroneously, assumed value for any and all hydrated biological materials).

4. Discussion

Lolium perenne (and presumably all grasses with this leaf morphology and these volume-fractions and moduli of the components) can thus be modelled as a system of high modulus parallel fibres in a low modulus matrix. The stiffness of the fibres is about the maximum recorded for wet cellulose (hemp is 3.5×10^{10} N m^{-2}) [3] and is thus probably typical.

The model based on these results has a number of biological and agricultural implications. In the past agronomists have been unable to ascribe stiffness or strength of grass to any particular features due partly to inappropriate analytical methods (such as expressing strength as breaking load divided by the dry weight in mg of a 5 cm length of leaf [4]) and thus have had to resort to correlations of strength with cellulose content and with sclerenchyma fibre content [5]. This paper shows unequivocally that the sclerenchyma is the dominant factor and that, therefore, apparently small changes in the volume-fraction of sclerenchyma will produce large changes in the stiffness and strength of the leaf.

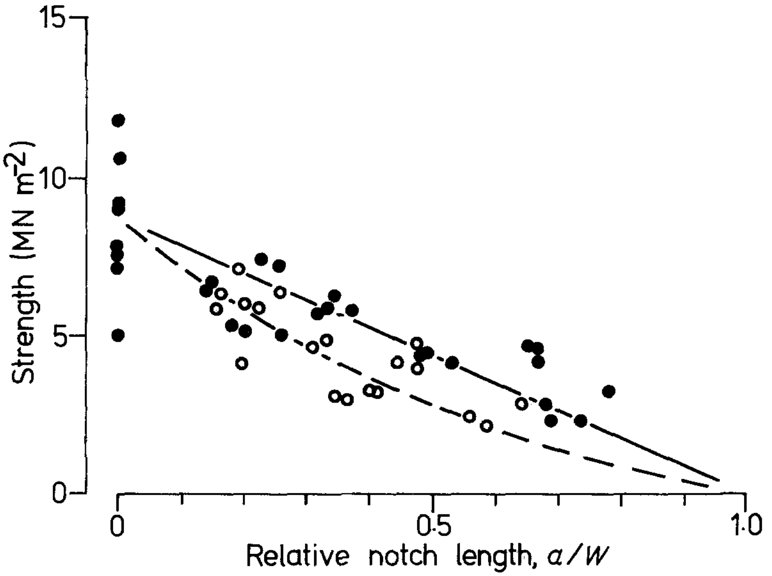

Figure 3 Results of: ●, edge-notch fracture tests, and ○, centre notch fracture tests. Ordinate and abcissa as Fig. 2.

The comparatively low modulus of the "matrix" is very probably also a factor in the resistance grass shows to trampling. Experiments not reported in this paper, in which the grass was bruised by dragging a blunt instrument (such as a ball about 3 mm diameter) across the leaf, or folding and unfolding the leaf, thus making a similar bruise of a type which might be caused by walking on a grass lawn, showed that this sort of damage has to be very extensive before it affects the fracture properties of the grass [6]. In most instances fracture of the bruised specimens occurred at the clamps. As long as the sclerenchyma fibres are intact, and they seem to be well protected by the rest of the leaf, the strength of the grass is unaffected.

The values calculated for specific work-of-fracture are low for a uniaxially orientated fibrous composite: for instance a continuous-fibre glass-fibre reinforced plastic has a fracture energy of the order of $10^5\,\mathrm{J\,m^{-2}}$ [7]. However, it should be noted not merely that the fibre volume-fraction is low (about 4.5%), but that the total solids content of the grass leaf is also very low (about 15% [5]). It is then apparent that the figure is probably as good as might be achieved. The com-

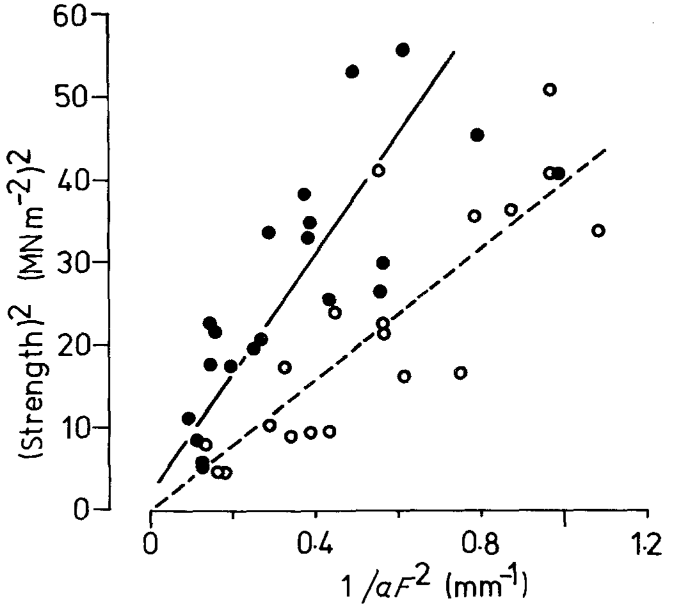

Figure 4 Data of Fig. 3 transformed according to the formulae in the text. The slope of the calculated regression lines is $K_c^2\pi$, hence K_c (the stress-intensity factor) can be calculated (Table II) symbols as Fig. 3.

TABLE II Constants of fracture for grass

Parameter (data for Fig. 4)	Type of damage introduced into grass leaf	
	Double edge-notched	Centre-notched
Stress-intensity factor, K_c (N m$^{-3/2}$)	1.564×10^5	1.144×10^5
Correlation coefficient, r	0.756	0.839
Specific work of fracture (J m^{-2})		
(a) $\nu = 0.3$	40.2	21.5
(b) $\nu = 0.5$	33.1	17.7

parison between edge- and centre-notching highlights the importance of the mid-rib, which contains about 20% of the total volume-fraction of fibre. This inhomogeneity clearly has a marked effect, even though in the double edge-notched specimens the mid-rib did not deflect the crack to a detectable degree. This may have implications for agronomists: if it is desired to reduce the fibre content of the grass (which will increase the digestibility), it should not be done at the expense of the mid-rib or the grass leaf will be weaker. Alternatively if it is desired to breed a grass which is easier to graze upon, then reducing the relative size of the mid-rib may be advantageous.

Finally, these results are relevant to the way in which animals graze. The aim of the animal when feeding is to gather the maximum amount of food with the least effort. With most plants and plant products (e.g., lettuce leaf, celery, apple, carrot, etc.) the teeth initiate a crack which can then be propagated with little effort [8]. (Of relevance here is that unpublished experiments from this laboratory show that apple skin is only moderately crack insensitive [9].) However, the introduction of a notch into a grass leaf does not produce a significant stress concentration, so this strategy is not the best for gathering grass. Grazers, then, seem to be broadly divided into two groups based on animal size. Large grazers, which are strong enough and large enough to be able to break the grass in tension, take hold of a clump of grass (the cow does this with its tongue) and pull vertically, often twisting the grass at the same time. This is similar to the way a human will pull grass by hand. Note that the teeth are expressly not used and may even be absent (e.g., sheep upper front teeth). Small grazers are not able to pull and break the grass leaf with such ease, if at all. They are armed with scissor-like teeth (e.g., the rabbit) or mandibles (e.g., the locust) and nibble or munch at individual leaves.

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