JOURNAL OF MATERIALS SCIENCE **35** (2000) 3553–3559

Mechanical properties of lettuce

G. A. TOOLE, M. L. PARKER, A. C. SMITH[†], K. W. WALDRON
Institute of Food Research, Norwich Research Park, Colney, Norwich, NR4 7UA, UK
E-mail: andrew.smith@bbsrc.ac.uk

The fracture properties of Spanish Iceberg and English Round lettuce tissues were investigated using a tensile test on notched specimens. The level of notch sensitivity was investigated for samples of differing colour and vein orientation. Vein orientation perpendicular to the test direction proved to be the most notch sensitive and samples with vein orientation parallel to the test direction proved to be very notch insensitive, samples with a diagonal (45°) orientation showed an intermediate response. This behaviour was interpreted in terms of the interaction of veins with the crack path. The strengths of English Round tissues were broadly comparable with those of Spanish Iceberg although the upper limits depended on vein orientation and were in the order: parallel > diagonal ≈ perpendicular. A similar ranking of vein orientation was found in estimates of stiffness.

1. Introduction

This study was designed to gain new insights into the texture of Spanish Iceberg (SI) and English Round (ER) lettuce by the measurement of mechanical properties. The SI lettuce has a closed dense structure, the leaves are tightly wrapped and interlocking, the texture is very crisp and the vascular tissues are numerous occupying the majority of the leaf spreading from the base to the top of each leaf. The ER lettuce has a loose open structure and the leaves are far thinner and have a flexible rather than a crisp texture. The vascular tissue is more sparse, and the veins spread outwards towards the edge of each leaf from the mid-rib at the centre. The lettuce leaf is an example of an extremely complex natural system. Although the leaves are a relatively–delicate structure, across which tears can be propagated easily, the conducting tissue and the associated fibres provide a number of different crack-stopping devices. Within the leaves of plants, the fracture path is deflected by the network of veins, giving a non-isotropic system, making it difficult to measure fracture properties. Early work studying the fracture of dicotyledonous plant leaves involved the breaking of cabbage leaves. Cabbages were dropped from different heights and a strong relationship between height or energy and the total length of crack in the leaves was shown [1].

Tensile-test specimens frequently involve an artificial notch to ensure the specimen fails away from the specimen grips. The notch may cause a stress concentration following the Griffith treatment which is inversely proportional to the square root of length of the flaw [2]. The notch sensitivity may be tested by examining the dependence of strength on notch size relative to specimen width. A notch–insensitive specimen is not weakened by a notch and maintains a constant strength when expressed relative to the unnotched area. There have been several studies on the notch sensitivity of grass, leaves and fruit skins [3–6]. The skin of apple, tomato and grape were described as moderately notch sensitive whereas most grass leaves were completely notch insensitive. Other work on notch sensitivity includes that of meat products, which showed that cooked beef muscle tested along the fibre direction was completely notch insensitive [7].

Studies of lettuce have generally been limited to the sensory attributes, general appearance, wilting, decay and physiological disorders conducted mostly during investigations on the packaging, processing and storage conditions [8–10].

In this study a tensile test was performed with a universal testing machine using specially cut test pieces in which a single edge notch had been made. The tensile strength was calculated as a function of notch size and an estimate of the Young's modulus was made from the least–notched samples. By conducting this test on a large number of graded lettuce samples of the two varieties with differing vein structure (thickness and orientation of veins), the differences in strength and stiffness and the notch sensitivity of strength were investigated.

2. Materials and methods

2.1. Sample preparation

The lettuces used during this experiment were bought fresh from a supermarket on the day of use. During experimentation they were stored in their plastic packaging in a refrigerator at 4°C, each leaf being removed just before use. Rectangular strips of both SI and ER lettuces were cut (10 at a time) with width between 8 and 10 mm and length greater than 40 mm. They were cut to give three different orientations of the veins relative to the major axis of the sample: parallel, diagonal (45°) and perpendicular (Fig. 1). Notches ranging from 1 mm to 6 mm long were cut at the midpoint of each sample using a razor blade. For each sample, the colour was

---

[†] Corresponding author

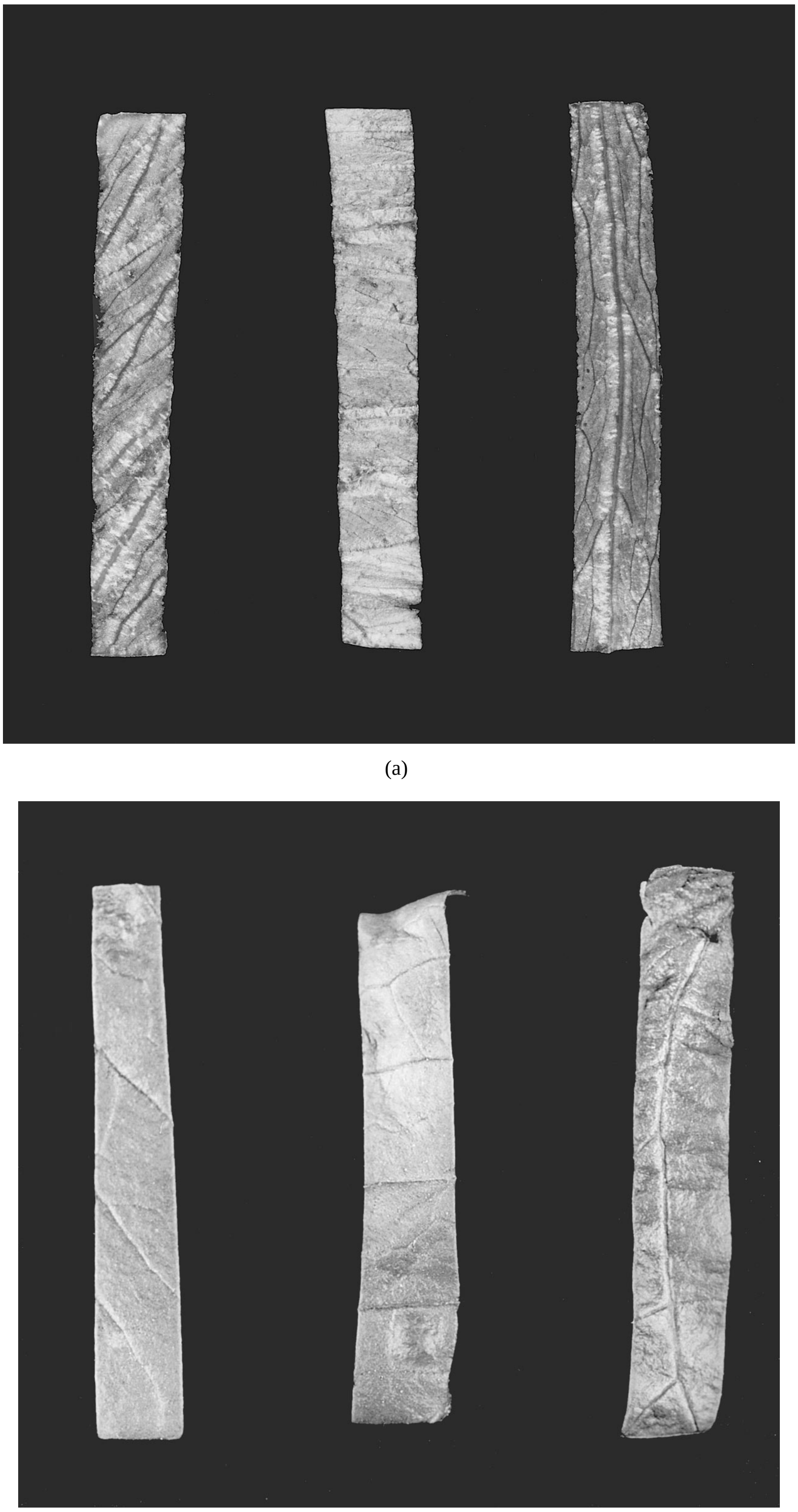
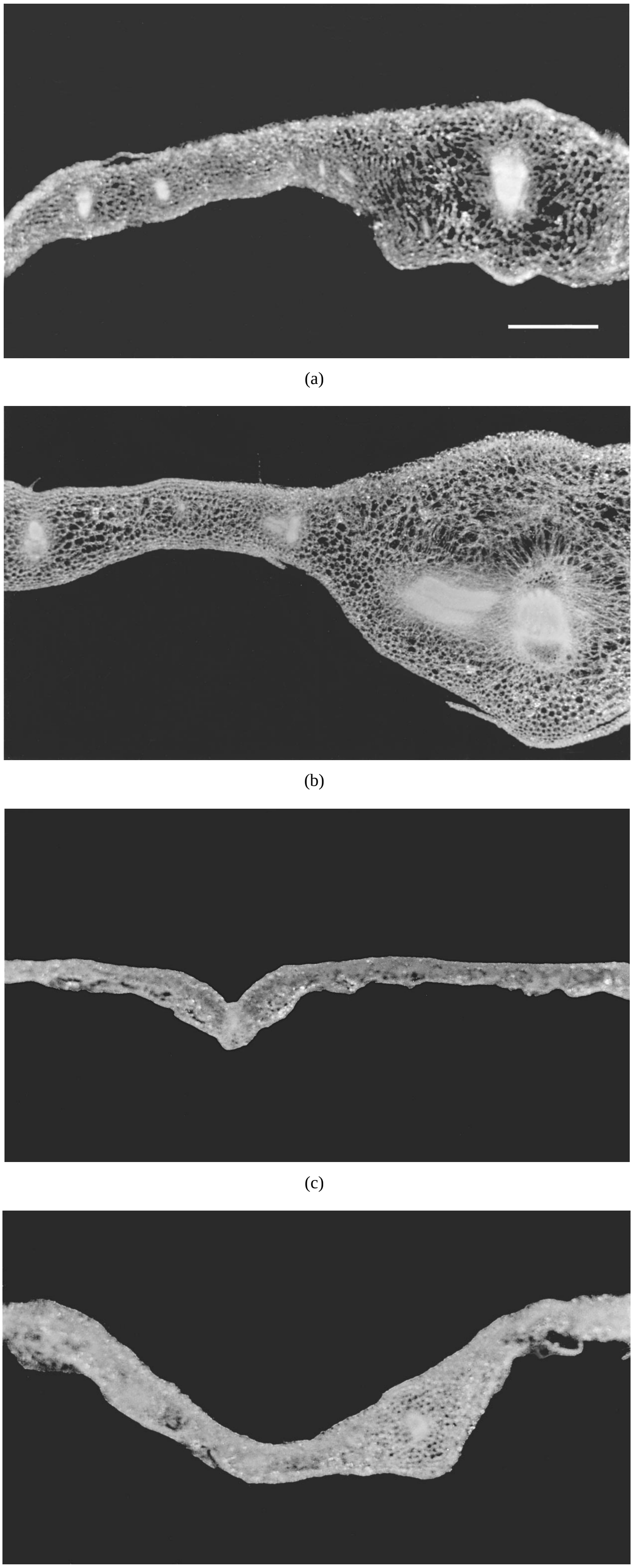


Figure 1 Lettuce sample strips showing (from left to right) diagonal, perpendicular and parallel vein orientation relative to the displacement direction (a) SI (b) ER.

graded green, green/white or white, and the width and thickness were measured using vernier callipers and a digital micrometer, respectively. The thickness was not uniform and varied with cultivar and position in the leaf as indicated by colour. An estimate of this variation was made by measuring the thickness of the vein and the thickness of the surrounding tissue in strips with parallel-oriented veins (Fig. 2).

2.2. Instrumentation

Tensile tests were carried out using a TAXT2 Texture Analyser (Stable Micro Systems, Godalming, Surrey, UK), and recorded (software Texture Expert) with a test speed of 0.5 mm s^{-1}. The clamps used to secure the samples were adjusted each time to exactly 30 mm apart, leaving approximately 5 mm of sample clamped at each end.



(a)

(b)

(c)

(d)

Figure 2 Cross sections of lettuce samples with veins oriented parallel to the test direction (a) SI green (b) SI white (c) ER green (d) ER white. (Scale bar = 1 mm).

2.3. Method

Each sample was placed into the Texture Analyser and carefully, but securely, clamped in place and a tensile test conducted. As the sample was pulled apart, propagating a crack through the tissue starting at the notch, the tensile force as a function of the distance was recorded and any observations during the deformation were noted. A total of 330 SI lettuce and 360 ER lettuce samples were analysed. The force versus distance data were recorded and used to measure: i) the maximum force required to propagate the crack for all samples, ii) the initial slope of the force–displacement curve for the smallest notched samples.

Young's modulus, E, was calculated from:

$$E = \frac{L}{t \cdot w}\frac{\mathrm{d}F}{\mathrm{d}x}$$

where L is the original length, t is the thickness, w is the width and $\mathrm{d}F/\mathrm{d}x$ is the initial slope of the force–displacement curve.

In order to compare the level of notch sensitivity for differing groups of samples, the strength, σ, of each sample was calculated:

$$\sigma = \frac{F_{\max}}{t \cdot (w - a)}$$

where $F_{\max}$ is the maximum force and a is the notch length. The value of σ was plotted against the relative length of the notch (expressed as a/w).

The stress intensity factor, K, is defined as:

$$K = \sigma_{\mathrm{nom}}(\pi a)^{1/2} Y(a/w)$$

where the nominal strength, $\sigma_{\mathrm{nom}} = F_{\max}/t \cdot w$ and $Y(a/w)$ is a geometrical constant [11]:

$$Y(a/w) = 0.265[1 - (a/w)]^4 + [0.857 + 0.265(a/w)]/[1 - (a/w)]^{3/2}$$

3. Results and discussion

Stiffness estimates from samples notched to $a/w = 10\%$ for SI and ER lettuce tissues showed an order: parallel > diagonal ≈ perpendicular. Values for SI were: parallel 4.4 MPa, diagonal 2.3 MPa and perpendicular 2.4 MPa and for ER: parallel 2.0 MPa, diagonal 1.1 MPa and perpendicular 1.4 MPa, with standard deviations of 0.4 MPa. Classical treatment of long fibre–reinforced polymers [12] shows that the stiffness falls off rapidly with increasing angle between test and fibre directions, decreasing little from 45° to 90°. Grass (*Lolium perenne* L.) has longitudinal and transverse Young's moduli of 554 and 14 MPa, respectively [3] and leaves (*Calophyllum inophyllum* L.) have Young's moduli of 50–68 MPa when tested across veins and 186–240 MPa along the veins [6], which are of greater magnitude and anisotropy ratio than the present results. The stiffness values for lettuce were more comparable with potato tissue which has a Young's modulus (measured in compression) of 3 to 6 MPa depending on turgor [13].

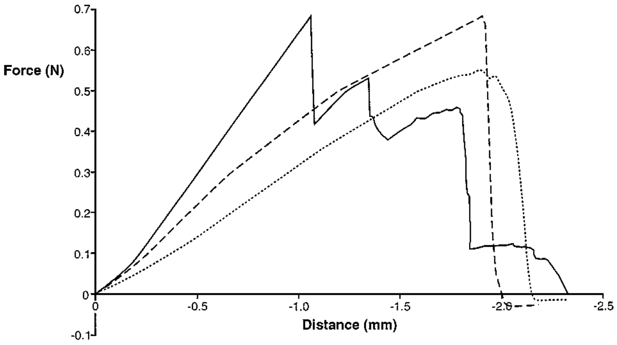


Figure 3 Graph showing the three 'fracture types'; (a) uneven tear at the notch (· · · ·), (b) clean break at the notch (- - - -), (c) break showing an increase in force at each vein (———).

The shape of the force–displacement curve gave a reliable indication of the nature of the failure. It was observed that the lettuce fractured primarily in three different ways: uneven tear at the notch, clean break at the notch, and break showing an increase in force at each vein (Fig. 3).

Graphs of strength as a function of relative notch size were plotted for the samples classified by orientation and colour (Figs. 4 and 5). Best fit straight lines were produced for each orientation (as shown in Figs. 4 and 5) and for each colour at each orientation, and their gradients calculated. The data were scattered for reasons of sample variability and inaccuracies in use of a stress formula applicable to uniform thickness test pieces. As a result the intercepts which represent the extrapolated unnotched strength were not considered. White-coloured tissue was generally the strongest and green-coloured tissue the weakest. From Figs. 4 and 5, the upper limits of strength of both ER and SI tissues, considering all colours, were found in the order: parallel > diagonal > perpendicular. Values were: SI—parallel 0.6 MPa, diagonal 0.4 MPa, perpendicular 0.3 MPa; ER—parallel 0.8 MPa, diagonal 0.3 MPa, perpendicular 0.2 MPa. This result is again consistent with classical treatments of long fibre–reinforced plastics [12, 14], where the tensile strength fell markedly as the angle between the test direction and the fibre orientation increased from 0 to 45° followed by a much slower decrease thereafter.

A horizontal straight line in Figs. 4 and 5 would indicate a notch insensitive sample, since the strength is constant as the width is decreased by introducing a notch. This means that any damage sustained by the sample does not greatly influence its ability to fracture. As the gradient of the line decreases, the notch sensitivity increases, thus indicating that the material is notch-sensitive and can be weakened by the presence of even small imperfections. Therefore the gradient of the line may be used to represent the level of notch sensitivity of the sample. Figs. 6 and 7 show histograms displaying the relative notch sensitivity of the various sample types by colour and orientation.

Samples with a perpendicular vein orientation produced lines with a negative gradient proving to be the most notch—sensitive orientation, although only slightly notch sensitive. Gradients relative to % a/w (±standard deviation) were -1.47 ± 0.30 kPa for SI

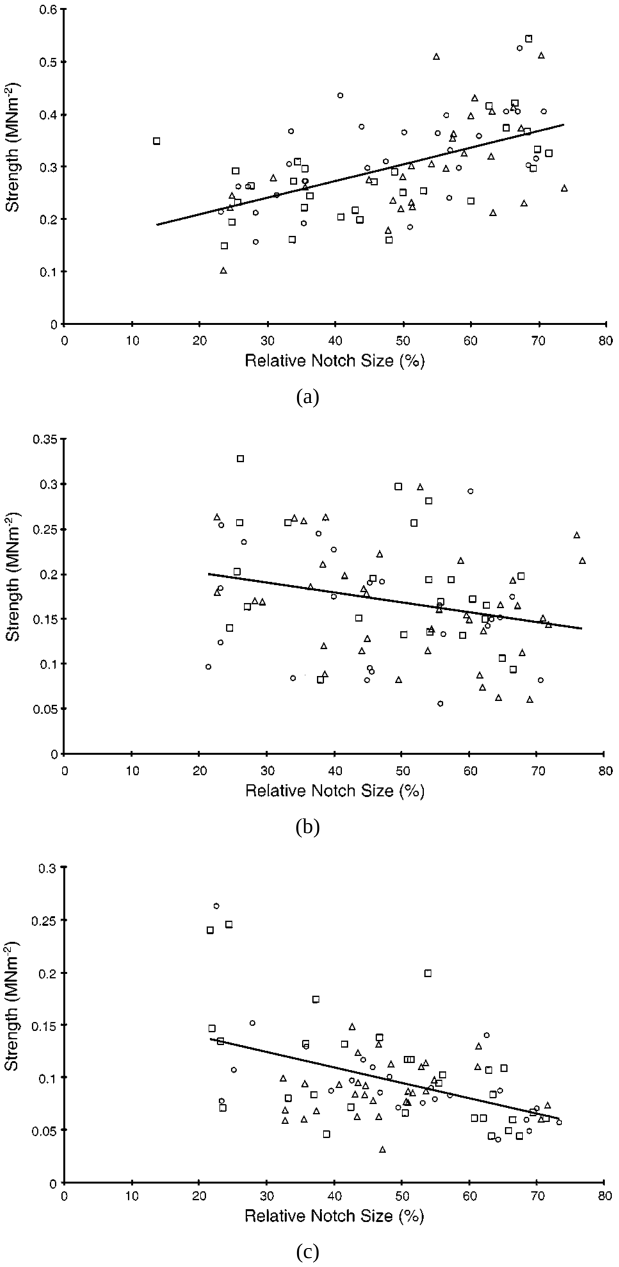


Figure 4 Strength of SI lettuce samples separated by orientation and colour (green □, green-white △, white ○). Orientation with testing direction (a) parallel (b) diagonal (c) perpendicular. Linear fits for each orientation are shown.

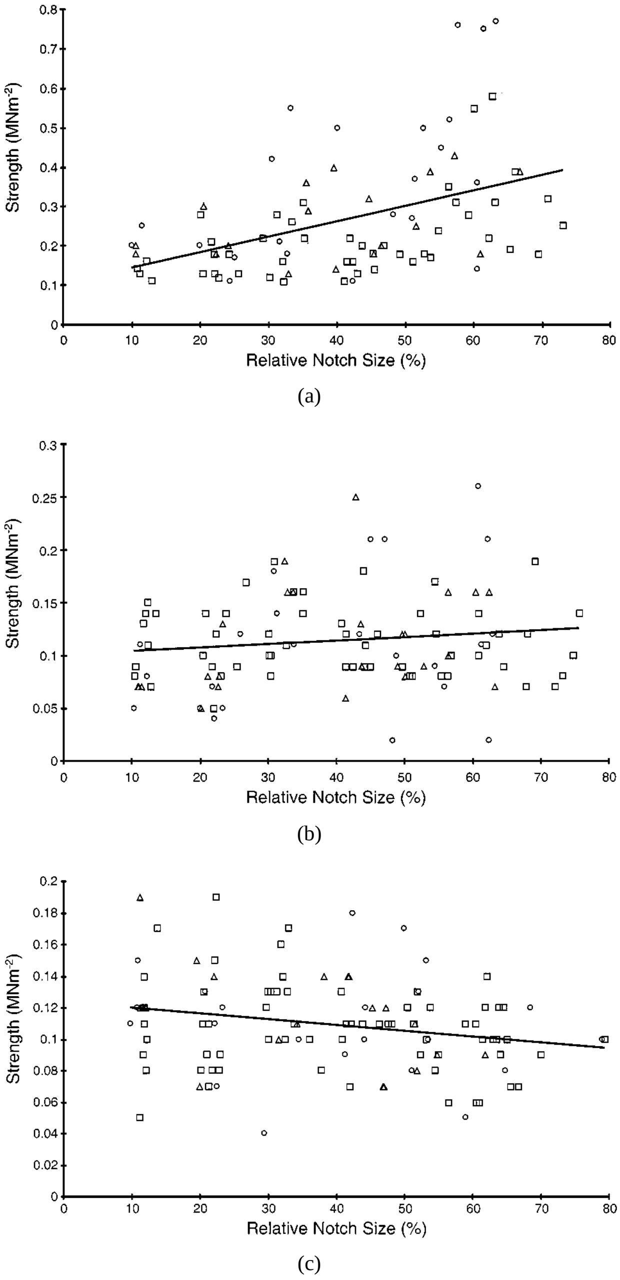


Figure 5 Strength of ER lettuce samples separated by orientation and colour (green □, green-white △, white ○). Orientation with testing direction (a) parallel (b) diagonal (c) perpendicular. Linear fits for each orientation are shown.

and −0.37 ± 0.15 kPa for ER in Figs 4 and 5, respectively. In most cases the crack propagated through lettuce parenchyma tissue, without encountering any veins, producing an uneven tear (Fig. 3(a)) rather than a clean break.

Samples with a parallel vein orientation produced lines with a positive gradient. Gradients relative to % a/w (±standard deviation) were 3.20 ± 0.52 kPa for SI and 3.95 ± 0.84 kPa for ER in Figs 4 and 5, respectively. This behaviour would not be expected in uniform test pieces and was neither conventionally notch sensitive or insensitive. This phenomenon was attributed to the observation that the propagating crack was more likely to encounter veins, thus the measured force depended less on the length of the notch and more on the size and strength of the veins. Referring again to the example of long fibre–reinforced composites, strength is

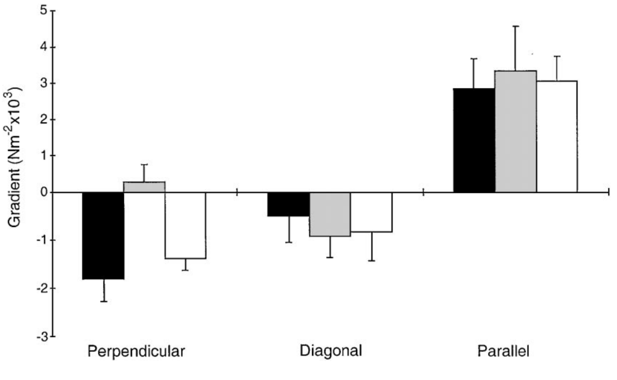


Figure 6 Histogram showing the gradients of Fig. 4, as a function of % notch length expressed relative to the sample width for SI for each orientation with testing direction and colour: green ■, green-white ▨, white □.

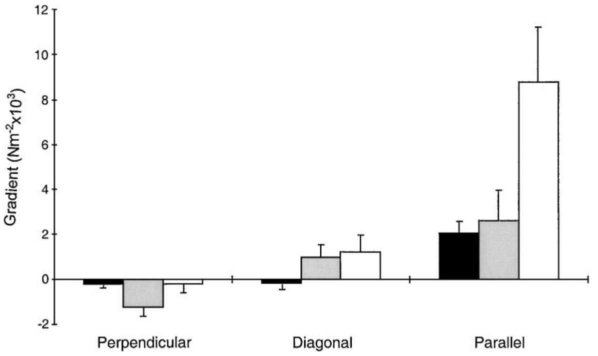


Figure 7 Histogram showing the gradients of Fig. 5, as a function of % notch length expressed relative to the sample width for ER for each orientation with testing direction and colour: green ■, green-white ▨, white □.

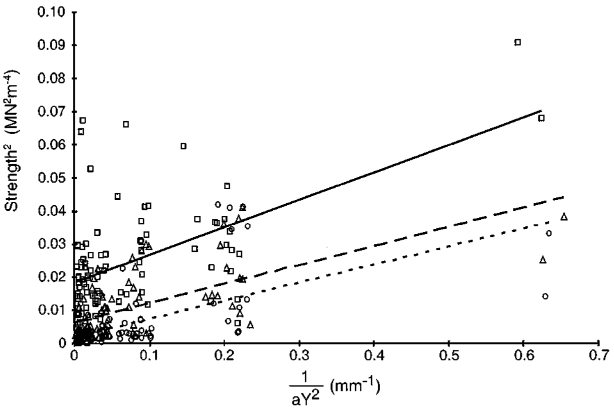


Figure 8 Square of nominal stress, σ^2_{nom}, as a function of $1/(aY^2)$ for SI for each orientation: Parallel □—□, Diagonal △– –△, Perpendicular ○···○.

influenced by the volume fraction of fibres and the fibre strength [14]. Consequently the breaking force would fall each time a vein is cut rather than decrease in proportion to the sample width remaining after notching. In the extreme case, if notching does not remove load-bearing veins then the strength (expressed relative to the unnotched width) would increase strongly with increasing notch size.

Fig. 2 shows that the veins were up to 5 times thicker than the surrounding tissue in white SI and twice as thick in white ER which highlights the inadequacy of using a single thickness value in the formulae for stiffness and strength. The influence of the veins was shown in the force–deflection curves which were generally a clean break (Fig. 3(b)) or a break showing an increase in force (Fig. 3(c)) as the crack crossed each vein.

The diagonal orientation of veins showed an intermediate notch sensitivity although the force–displacement response exhibited all of the types shown in Fig. 3. Gradients relative to % a/w (±standard deviation) were -1.09 ± 0.45 kPa for SI and 0.32 ± 0.24 kPa for ER in Figs. 4 and 5, respectively. In addition to crossing veins, the other observations were that the direct crack path did not include veins and that the crack was diverted along veins.

In comparison, the strength of grass (*Lolium perenne* L.) was much higher at some 9 MPa, showing little or no notch sensitivity [3]. The tensile strength of other grasses varied from 5.0 to 45.9 MPa, ranging from notch insensitive to significantly sensitive (*Stipa gigantea*) [5]. The tensile strength of leaves (*Calophyllum inophyllum* L.) was greater when loaded along compared to across secondary veins [6], consistent with the lettuce results in Figs. 4 and 5. Values were 5–7.5 MPa and 2–2.5 MPa, respectively, both of which showed little notch sensitivity. The strength of apple skins was over 4 MPa for unnotched samples and grape and tomato skin strengths were lower at 1.5 MPa, although they were all described as moderately notch sensitive [4]. Other tissue strengths determined in tension include 0.5 to 1.5 MPa for carrot [15] and 0.4 MPa for potato [16].

The stress intensity factor, K, was calculated from the slopes of σ^2_{nom} plotted against $1/(aY^2)$ and gave values (±standard deviation) of 0.013–0.016 ± 0.006 MN m$^{-3/2}$ for SI (Fig. 8) and 0 to 0.007 ± 0.003 MN m$^{-3/2}$ for ER, with no significant variation with orientation. In most cases the linear fits did not pass through the origin as is also evident in other data [6], while the applicability of the calculation of K to anisotropic materials has been questioned [5]. The above data may be compared with K of 0.156 MN m$^{-3/2}$ for grass (*Lolium perenne* L.) [3], although other grasses had K values of 1.75 to 6.99 MN m$^{-3/2}$ [5], and 0.122 and 0.394 MN m$^{-3/2}$ across and along the fibres, respectively, in leaves (*Calophyllum inophyllum* L.) [6].

4. Conclusions

A partial analogy may be made between the fracture behaviour of lettuce leaves and that of fibrous composite materials. Within a leaf, the bundles of vascular tissue (veins) which transport water and nutrients along the leaf are seen as the reinforcing fibres within a matrix of tissue (parenchyma). The interface between these two phases provides opportunities for energy to be absorbed; as a crack opens, the fibres (vascular bundles) extend across it dissipating energy by their own deformation or by friction as they pull out from the bulk matrix of the material.

The degree of notch sensitivity is important in comparing natural materials such as lettuce cultivars since a small crack may severely weaken a highly notch-sensitive material. Although the data shows some evidence for SI tissue being stiffer and stronger in tension than the ER variety, orientation of the veins affects strength and stiffness in both types with orientation parallel to the test direction imparting greater strength and stiffness than diagonal or perpendicular orientations.

Veins perpendicular to the test direction conferred a notch sensitivity on tissues, particularly for SI, which failed by uneven tearing dictated chiefly by the material between the veins. Orientation of veins parallel to the test direction produced a notch insensitivity accompanied by single clean break or breaking of multiple veins. The veins make a major contribution to the tissue strength as indicated by their thickness relative to the surrounding tissue. This leads to inaccuracies in the calculation of the strength based on a simple sheet of constant thickness. There was an apparent increase in strength with increasing notch size when based on the unnotched width and the thickness of the tissue. The dominance of the veins means that edge notching does not reduce these load bearing elements simply in proportion to the remaining unnotched width of tissue.

Acknowledgement

This work was funded by the Biotechnology and Biological Sciences Research Council through their Competitive Strategic Grant and a studentship to G.A.T.

References

1. J. E. HOLT and D. SCHOORL, *J. Text. Studies* **14** (1983) 99.
2. A. G. ATKINS and Y. W. MAI, "Elastic and Plastic Fracture; Metals, Polymers, Ceramics, Composites, Biological Materials" (Ellis Horwood, Chichester, 1985).
3. J. F. V. VINCENT, *J. Mater. Sci.* **17** (1982) 856.
4. *Idem.*, in "Advances in Botanical Research," Vol. 17 edited by J. A. Callow (Academic Press, London, 1990) p. 235.
5. *Idem.*, *J. Mater. Sci.* **26** (1991) 1947.
6. P. W. LUCAS, M. F. CHOONG, H. T. W. TAN, I. M. TURNER and A. J. BERRICK, *Phil. Trans. Roy. Soc. Lond. B* **334** (1991) 95.
7. P. PURSLOW, in "Food Colloids," edited by R. D. Bee, P. Richmond and J. Mingins (Royal Soc. Chem., London, 1989) p. 246.
8. F. ARTÉS and J. A. MARTÍNEZ, *Lebensm. -Wiss. u.-Technol.* **29** (1996) 664.
9. H. HEIMDAL, B. F. KÜHN, L. POLL and L. M. LARSON, *J. Food Sci.* **60** (1995) 1265.
10. A. A. ALSADON, *Hortscience* **28** (1993) 159.
11. H. TADA, P. PARIS and G. IRWIN, "The Stress Analysis of Cracks Handbook" (Del Research Corporation, St. Louis, Missouri, 1981).
12. P. POWELL, "Engineering with Polymers" (Chapman and Hall, London, 1983).
13. S. HILLER and G. JERONIMIDIS, *J. Mater. Sci.* **31** (1996) 2779.
14. D. C. PHILLIPS and B. HARRIS, in "Polymer Engineering Composites," edited by M. O. W. Richardson (Applied Science, London, 1977) p. 45.
15. A. McGARRY, *Ann. Botany* **75** (1995) 157.
16. K. W. WALDRON, A. C. SMITH, A. NG, A. J. PARR and M. L. PARKER, *Trends Food Sci. Technol.* **8** (1997) 213.

Received 14 May
and accepted 15 December 1999