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Fracture in potato tuber parenchyma

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Experiments have been carried out to assess the fracture behaviour of potato tuber parenchyma tissue from two different varieties (cvs. King Edward and Record) in three different turgor states (turgid, fresh and flaccid). Methods included wedge-penetration fracture tests, razor-blade cutting tests, ball indentation tests and compression tests. Turgor was manipulated by immersion of fresh tissue in osmotica of known concentration, and assessed by means of cell pressure probing. No significant differences in properties were ascribed to the difference in variety. Changes in water status were responsible for appreciable changes in the fracture properties of the tissue. Values of compressive Young's modulus and work of fracture were combined to predict critical crack lengths for different turgor states under given levels of applied stress below the yield stress.

1. Introduction

Mechanical stressing of potato tuber parenchyma tissue may give rise to damage, either in the form of bruising, characterized by the disruption of a volume of mutually adjacent cells, or in the form of cracking, in which disruption is limited to a single plane within the tissue. Analogous behaviour may be observed in engineering materials such as mild steel, which can fail by plastic yielding of a localized volume of metal, or by brittle propagation of a crack along a single plane. In the case of steel, the likely nature of failure is determined by temperature, by the presence of stress-raising defects, and to a lesser extent, by alloying additions. It is very often the case that brittle failure occurs at stress levels far lower than those required to initiate bulk plastic yielding. In potato tuber parenchyma, factors affecting the precise form of tissue failure are still largely unknown, although cultivar, temperature [1], agronomy, water status and rate of loading may each have an effect. Two cultivars, "Record" and "King Edward", were selected for a recent study on the basis of their differing susceptibility to bruising and cracking [2, 3]; cv. "Record" was reported to be particularly prone to blackspot bruising, while cv. "King Edward" was described as being most likely to fail due to shatter cracking. It was decided to use these same cultivars in the tests to be described.

The effects of turgor pressure on the quasi-static tensile and compressive stiffness of potato tuber parenchyma have been well documented [4–6], although the non-linear force/deflection behaviour of the tissue makes unequivocal determination of stiffness difficult. Turgor pressure has also been found to affect the yield strength of potato tissue [6], higher turgor pressures reducing tissue strength under constant strain-rate uniaxial loading.

The two parameters controlling crack initiation in a perfectly brittle material exposed to a given level of applied tensile stress are the stiffness, (which affects the amount of energy stored per unit volume under a given strain), and the work of fracture (which is the energy required to create unit area of crack surface). Thus, [7]

$$L_c = \frac{2ER}{\pi\sigma^2} \quad (1)$$

where E = Young's modulus, R = work of fracture, σ = applied tensile stress and L_c = critical crack length.

In this case, the critical crack length represents the size of flaw present in the material which will just cause propagation of a free-running crack. The above equation is strictly applicable only to brittle materials for which plastic yielding in the crack tip zone is negligible. The Orowan–Irwin equation [8, 9] attempts to allow for this by the addition of a plastic work term to the surface energy term:

$$L_c = \frac{E(2R + \gamma_p)}{\pi\sigma^2} \quad (2)$$

where E = Young's modulus, R = work of fracture, σ = applied tensile stress, γ_p = plastic work done per unit area of crack extension, and L_c = critical crack length.

In order to assess the susceptibility of potato tissue to cracking, knowledge of the work of fracture and of Young's modulus is essential, as per Equation 1 above. It would be useful to include the plastic work term of Equation 2, but no technique was available for its direct measurement, hence this was not attempted. Yield stress, *per se*, is also of interest if local failure

occurs via plastic flow, before sufficient energy has been stored in the material to "fuel" propagation of a crack.

A series of tests was planned to measure the work of fracture, Young's modulus and compressive yield stress of samples of potato tuber tissue. As an adjunct to the fracture tests, cutting tests were also carried out using a thin razor blade.

The object of these different tests was to assess the effects of water status on tuber tissue fracture behaviour in the two potato varieties "Record" and "King Edward", with a view to explaining the previously-reported differences in observed tuber impact damage.

2. Materials and methods

2.1. Sample preparation

Potatoes were planted on 29/4/94 in ground prepared and fertilized with 17/17/17 NPK at 600 kg acre^{-1}. Planting was in rows separated by 0.9 m, plants being spaced 0.6 m apart in each row. Weed control was manual, and the crop was flooded regularly with a hosepipe. Tubers were harvested manually on 24/10/94, and stored for 16 days at 1–2 °C prior to testing.

Tissue water status was categorized as "fresh", "turgid" and "flaccid". "Fresh" tissue was tested immediately after removal from store without further treatment. "Turgid" tissue samples were cut to shape, then immersed for approximately 24 h in buffered demin. water (0.02 M KH_2PO_4/0.02 M K_2HPO_4) prior to testing. "Flaccid" tissue samples were similarly prepared, but immersed for 24 h in a 0.3 M mannitol solution, also buffered (0.02 M KH_2PO_4/0.02 M K_2HPO_4), prior to testing.

Samples for work of fracture and work of cutting tests were in the form of parenchyma tissue cubes, 20 mm on a side. These were prepared using a fine-bladed saw in a mitre-frame, care being taken to avoid areas of pith where possible. Every cube was marked to ensure that each test was carried out with the crosshead of the mechanical test machine moving parallel to the heel-rose axis of the tuber tissue sample.

Samples for compression test were produced in the form of right-ended cylinders, nominally 8.5 mm in diameter, using a stainless steel cork-borer pressed into a tuber slice cut perpendicular to the heel-rose axis. Each cylinder was subsequently trimmed to a length of approximately 12 mm using a razor-blade guillotine.

Samples for ball-indentation tests were in the form of tuber slices, nominally parallel-faced and 10 mm thick, cut perpendicular to the heel-rose tuber axis.

2.2. Mechanical tests

A universal mechanical test machine (Davenport-Nene DN10, with v.6.4 control software) was used to perform the various tests. Experiments were carried out on tissue samples in each of the three turgor states on three separate days. Each sequence of tests was done on pairs of tissue samples of the two varieties taken in a random order, and the order in which the four different tests were carried out was also randomized in the form of a latin square (see Appendix) to minimize possible systematic effects during testing.

2.2.1. Fracture tests

The technique used was based upon that used by Khan [10] and described by Vincent [11].

For each test, a sample cube of tissue, prepared as previously described, was placed upon a stationary horizontal metal platen within the universal mechanical test machine. The tests utilized a 45 degree included angle perspex wedge, which was introduced into the sample tissue cube from above, at its centreline, parallel to one edge. The wedge was mounted on a 260 N capacity load cell, itself attached to the underside of the crosshead. The length of the "cutting edge" of the wedge was in excess of the sample cube size, ensuring that progressive advance of the wedge effectively bisected the cube.

The basic method relied upon an estimation of the amounts of energy stored within the sample prior, and immediately subsequent, to the spontaneous propagation of a crack through the tissue. In order to obtain these values, a technique was adopted in which the perspex wedge was advanced into the tissue to increasing depths on successive cycles, and withdrawn between each advance until zero load was registered, prior to initiation of the next cycle. Sudden and rapid crack propagation ahead of the wedge signalled immediate withdrawal of the wedge from the sample, whilst recording the force/deflection trace.

The universal test machine was programmed to apply cycles of wedge advance and withdrawal at a rate of 25 mm min^{-1}, advancing further into the sample by 1 mm increments until the sample was divided in two. The immediate withdrawal of the wedge from the sample after the occurrence of a significant free-running crack was initiated manually by the operator. Not all samples failed by rapidly-propagating cracks; many failed with no obvious sign of large-scale cracking ahead of the wedge, and in these cases, a duplicate sample was often tested in addition to the first sample, in an attempt to obtain a result.

In those samples which failed by rapid cracking, it was necessary to estimate the depth of the free-running crack, as a prelude to the calculation of the nominal crack surface area. The final depth of the crack could not be determined from the force/deflection trace, since the crack tip was by then well in advance of the wedge-tip. Thus, it proved necessary to recover each cube immediately after testing, to stain the crack zone with blue water-based ink, then to section the cubes perpendicular to the wedge axis with several nominally equi-spaced cuts. It was noted that the crack seldom advanced uniformly to the same depth across the cube, hence crack depths were measured on the several individual sections using a vernier calliper, and a mean value taken as the final crack depth, d_{end}.

2.2.2. Cutting tests

A single-edged razor blade, length 39 mm, depth 12.5 mm, thickness 0.25 mm, with a 1 mm bevel of

included angle 14°, was attached (edge-downwards) to the threaded spigot of a 10 N load cell, itself attached to the underside of the machine crosshead. In each test, a cube of tissue, prepared as previously described, was placed on a stationary horizontal platen within the universal mechanical test machine, centrally beneath the razor blade edge. A "U"-shaped wire restraint was lowered to just touch the top of the tissue cube outside the projected zone of cutting, thus preventing the lifting of the cube during subsequent blade withdrawal. The blade was then lowered into the tissue cube at a steady rate of 25 mm min^{-1} to a depth of 8 mm, and withdrawn at the same rate until clear of the tissue, force/penetration data being recorded.

2.2.3. Ball indentation tests

For each set of tests, a 10 mm thick slice of potato tissue, prepared as described above, was placed upon a flat metal platen within the universal mechanical test machine. A 6 mm diameter steel ball, attached to a shallow recess in the end of a metal rod, was mounted via a 260 N load cell onto the test machine crosshead.

Downward movement of the crosshead caused the steel ball to penetrate the surface of the potato tissue to a depth just greater than the ball radius. Care was taken to position the slice relative to the ball, such that indentations were at least two ball diameters distant from slice edges and avoiding areas of pith within the tissue. Three tests were carried out on each slice in three separate positions, the force/penetration behaviour being recorded in each case.

2.2.4. Compression tests

In each case, a sample tissue cylinder, prepared as previously described, was placed, flat end down, on a stationary metal platen within the universal mechanical test machine. A horizontal platen, attached to the cross-head via a 260 N load cell, was then lowered at a constant rate of 2 mm min^{-1} until the sample yielded, the force/deflection behaviour being recorded.

2.2.5. Single cell pressure probe tests

As a direct indicator of tissue water status, the vacuoles of individual cells close to the surface in several different representative samples of potato tissue were probed directly for turgor pressure measurement. The technique used is well-established, following that of Husken *et al.* [12]. Some difficulty was experienced in obtaining clear readings from this apparatus, hence the number of measurements made was of necessity limited. These measurements were made after the mechanical test programme on untested cubes of tissue. Results are shown in Table 5.

3. Results

3.1. Mechanical tests

3.1.1. Assessment of raw graphical data

All the mechanical test results were in the form of force/deflection or force/penetration data, although the specific information yielded by each of the four types of test was different. In order to compare the behaviour of tissue samples, it was necessary to extract relevant numerical parameters from the raw graphical data in each case. The parameters were chosen as shown in Table I.

3.1.2. Fracture tests

Fig. 1 shows the final two cycles from a typical plot of force versus wedge penetration during a fracture test. The area beneath each unloading curve is broadly indicative of the recoverable mechanical energy available at the start of unloading. The balance of the total area beneath the loading curve represents the energy irreversibly lost in viscous processes (hysteresis). Point "B" is the point at which rapid crack propagation commenced, and point "A" is defined as a point on the penultimate unloading curve of equivalent load to point "B". In the case of unloading without cracking, the energy available at point "A" is given by area *a*, whereas for the case of unloading post-cracking, the energy recovered in unloading from a similar load level (point "B") is given by the lesser area *b*. Assuming that the energy stored within the sample is similar on the two consecutive loading cycles, the energy dissipated by the crack, E_{crack}, is given simply by the difference in recovered energies, $(a - b)$. It then remains to relate this energy dissipation to the surface area of the crack produced. The new crack surface area was calculated as follows. It was assumed that the

TABLE I Parameters extracted from raw graphical data

Test type	Parameter measured	Symbol used	Units
Fracture tests	Work of fracture	R	$J\,m^{-2}$
Cutting tests	Work of cutting (maximum)	$R_{cut_{max}}$	$J\,m^{-2}$
	Work of cutting (minimum)	$R_{cut_{min}}$	$J\,m^{-2}$
Ball indentation tests	Yield stress	σ_y	MPa
Compression tests (see Fig. 6)	Stiffness "A" (initial maximum)	E_{init}	MPa
	Stiffness "B" (central (minimum)	E_{cent}	MPa
	Stiffness "C" (final maximum)	E_{fin}	MPa
	Failure stress at "D"	σ_{fail}	MPa
	Failure strain at "D"	ε_{fail}	%

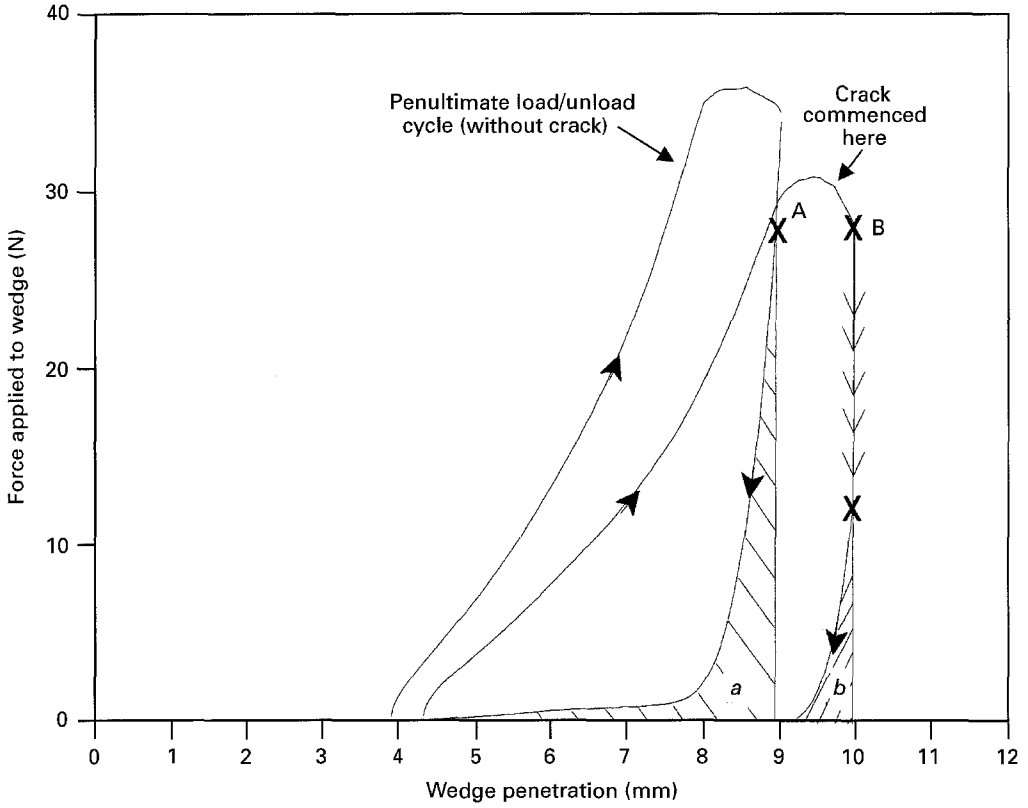


Figure 1 Final two load/unload cycles from a typical wedge fracture test.

position of the wedge cutting-edge at the point of initiation of a free-running crack, d_{start}, was indicative of the starting position of the crack, and this position could be read from the force/deflection trace as the point coincident with a sudden rapid decrease in load at the start of crack propagation (Point "B" in Fig. 1). The mean final crack depth, d_{end}, was that measured as described in 2.2 above.

The total nominal crack surface area, a_{crack}, was then given by:

$$a_{crack} = 2\,(d_{end} - d_{start})\ \text{(cube depth)}$$

and the work of fracture, R, was then obtained by dividing the energy dissipated by the total nominal crack surface area, thus

$$R = E_{crack}/a_{crack}$$

3.1.3. Cutting tests

Load/blade displacement curves from representative cutting tests on potato tissue in various turgor states are shown in Fig. 2. For "flaccid" tissue samples, it can be seen that the force peaked as the blade entered the tissue, dropping, then rising again to a substantially constant plateau (see Fig. 2a). Withdrawal of the blade required negligible force, as evidenced by the traces for withdrawal of the blade to zero displacement. In the cutting of "fresh" tissue, a similar force peak was registered as the blade entered the tissue, but there was a slight increase in cutting force with increasing penetration of the blade (see Fig. 2b). The return traces here show that a small force was required in order to withdraw the blade from the cut, diminishing to zero at the point of complete blade withdrawal in each case. The cutting of "turgid" tissue produced a similar local peak force, and subsequent force reduction, associated with initial blade penetration. However, increasing penetration of the blade into the tissue required progressively higher forces, ultimately exceeding the initial force peak by approaching a factor of three (see Fig. 2c). Blade withdrawal force was also higher than that measured for "flaccid" or "fresh" tissue.

Fig. 3 shows the same load versus blade displacement curves, normalized by subtraction of the withdrawal force from the penetration force for each displacement. As can be seen, the effect is to somewhat reduce the apparent differences in cutting force due to changes in turgor. Nevertheless, such differences were still appreciable, and doubtless reflect the greater bending stiffness of the "turgid" tissue requiring greater force to accommodate the blade thickness.

Work of cutting equates to the area beneath the force/penetration curve in each case. In view of the non-linearity of the traces, it was decided to extract two parameters for comparison, maximum work of cutting, $R_{cut_{max}}$, and minimum work of cutting, $R_{cut_{min}}$, each based on the areas beneath selected half-millimetre lengths of force/blade insertion trace.

3.1.4. Ball indentation tests

Ball indentation tests were carried out on tissue samples with the specific intention of establishing the local yield strength of the tissue.

These tests were based on the well-known Brinell indentation test, commonly used to measure the hardness of metals. Although "hardness" itself is an arbitrary parameter, dependent to some degree on the method of measurement, it is of value when comparing a given material in differing conditions, and has experimentally been found to correlate closely with the yield strength of the material as measured by

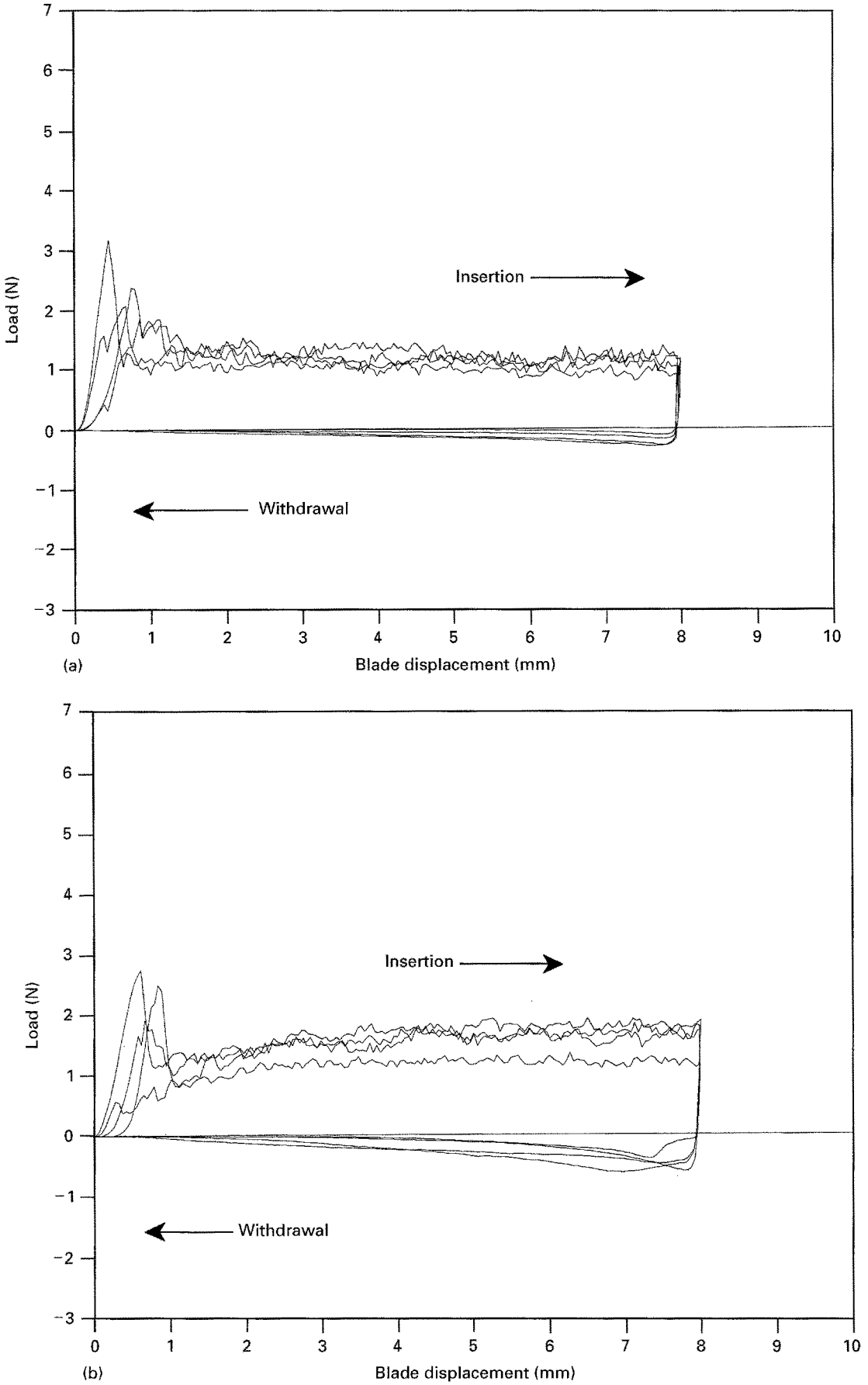


Figure 2 Load versus blade displacement curves for cutting of tissue cubes, (cv. Record), showing the effect of turgor. (a) Flaccid, (b) fresh, and (c) turgid.

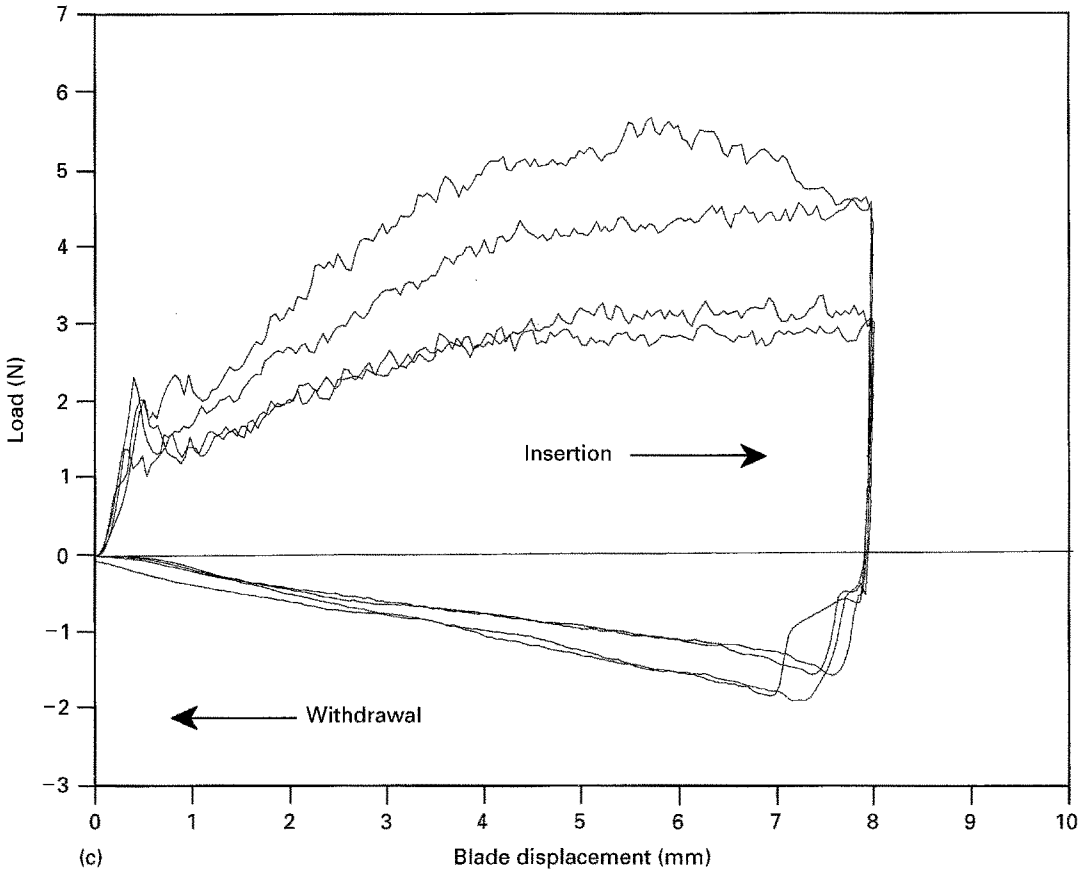


Figure 2 Continued

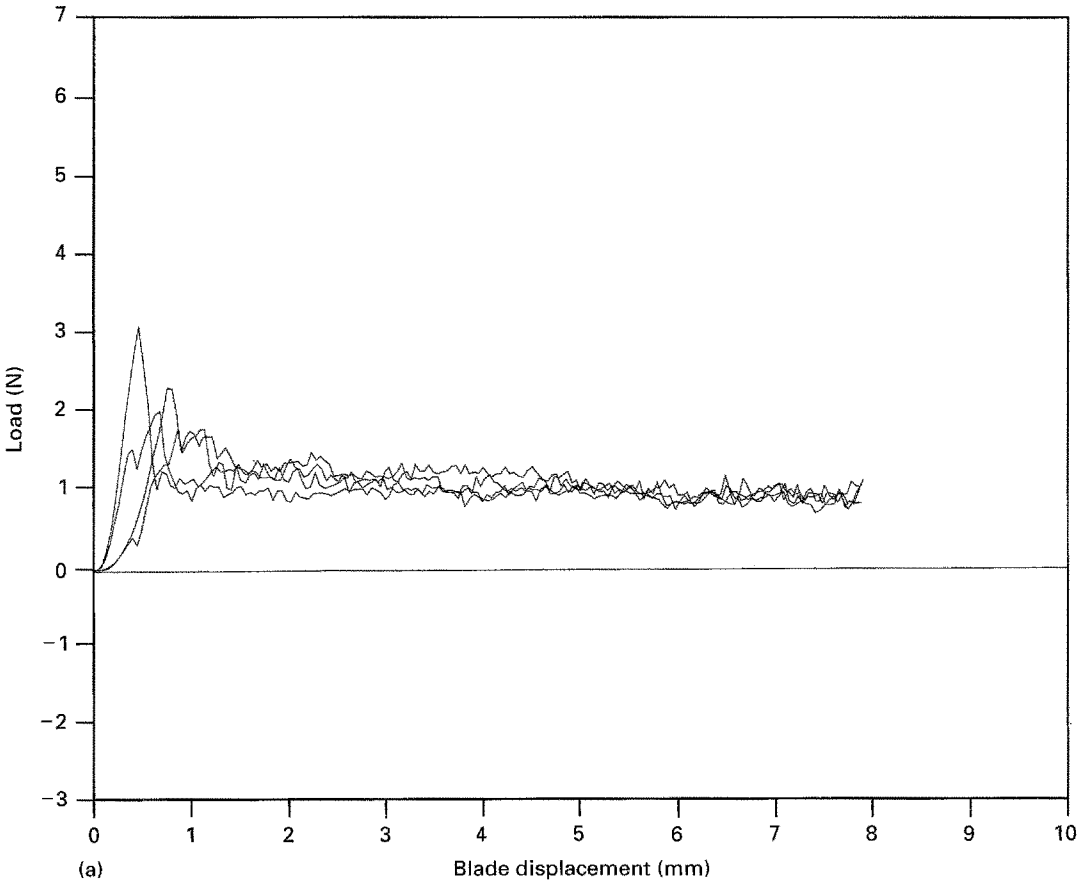
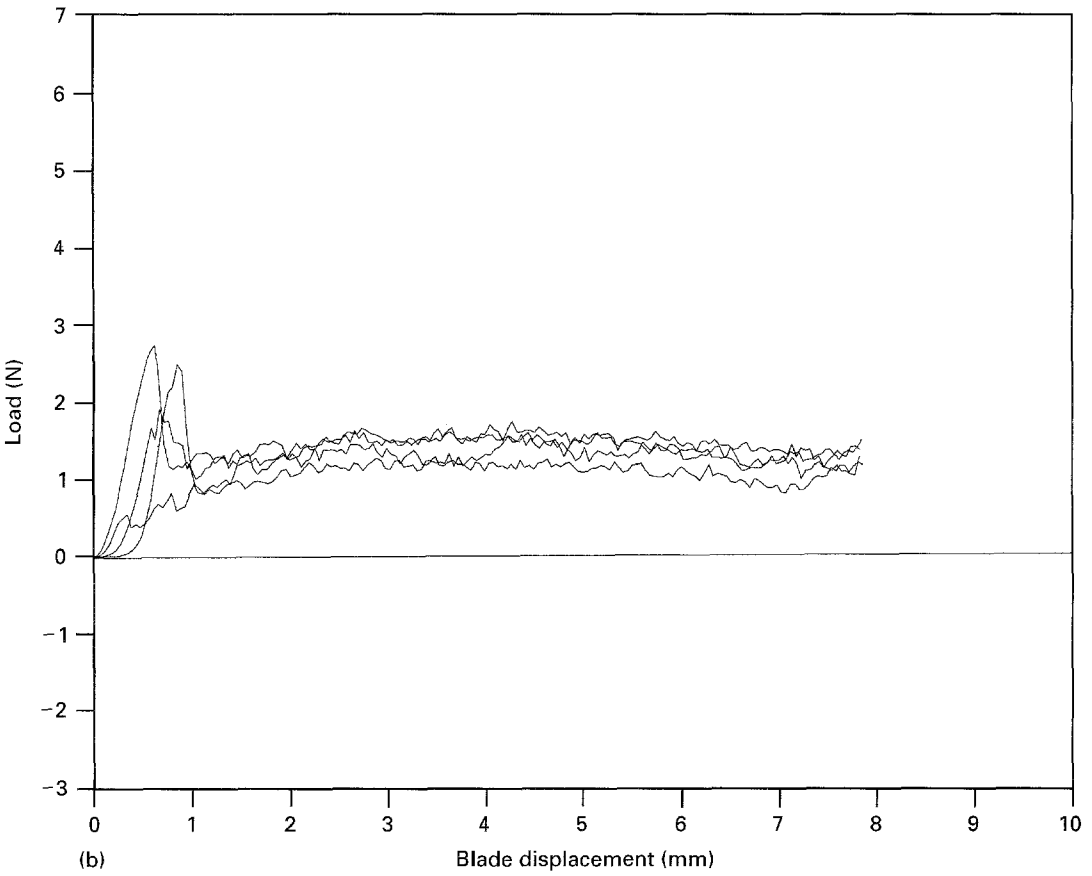


Figure 3 Load versus blade displacement curves for cutting of tissue cubes, (cv. Record), showing the effect of turgor. (Load values normalized by subtraction of blade withdrawal load from insertion load at each displacement point). (a) Flaccid, (b) fresh, and (c) turgid.



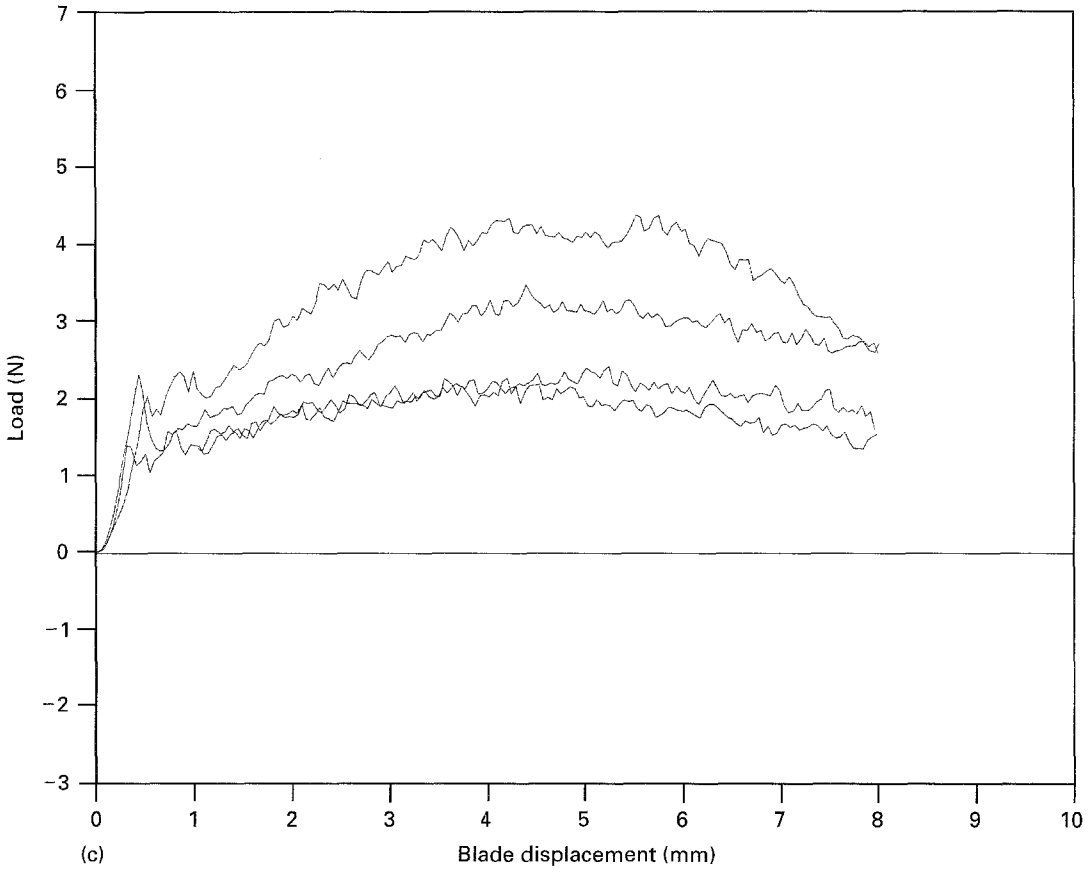


Figure 3 Continued

compression testing [13]. The depth of indentation, h(mm), for a given load, F(N), applied to a ball of diameter D(mm), is related to the Brinell hardness, HB, by

$$\mathrm{HB} = \frac{F}{\pi D h}\,\mathrm{N\,mm^{-2}}$$

and the equivalent yield stress, σ_y, is given by:

$$\sigma_y = \frac{1}{2.85}\frac{F}{\pi Dh}\,\mathrm{N\,mm^{-2}} \quad (3)$$

A typical ball indentation test force/penetration curve is shown in Fig. 4. It was decided to assess the depth of indentation, h, at a standard applied load, F, of 25 N, a load typically falling within the quasi-linear portion of the curves. Substituting these values in Equation 3 above enabled the calculation of a yield stress, σ_y, in each case.

3.1.5. Compression tests

The non-linear nature of the stress/strain behaviour of potato tissue in compression is evident from Fig. 5, which shows typical curves for "fresh", "turgid" and "flaccid" tissue samples. In order to make comparisons between the different curves, it was necessary to define parameters of interest. The clearest parameter for comparison was failure stress, and this was defined as the stress recorded immediately preceding the first sudden drop in stress heralding failure. As a basis for

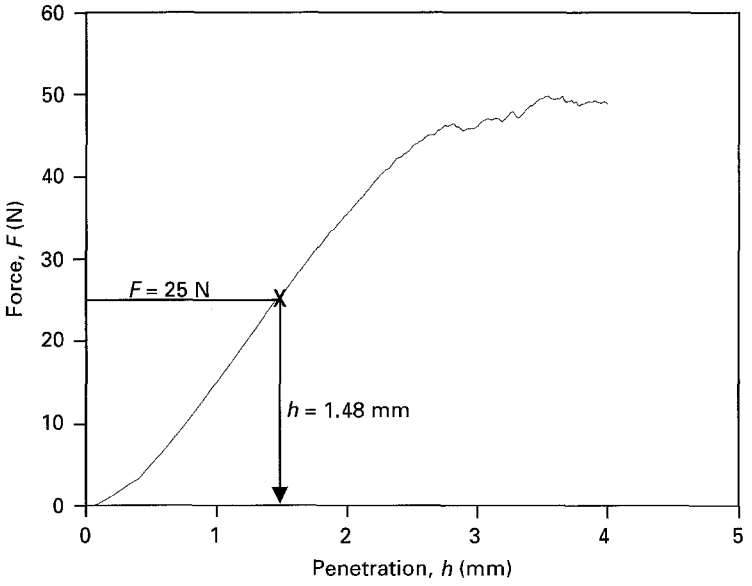


Figure 4 Typical load/penetration curve from a ball indentation test.

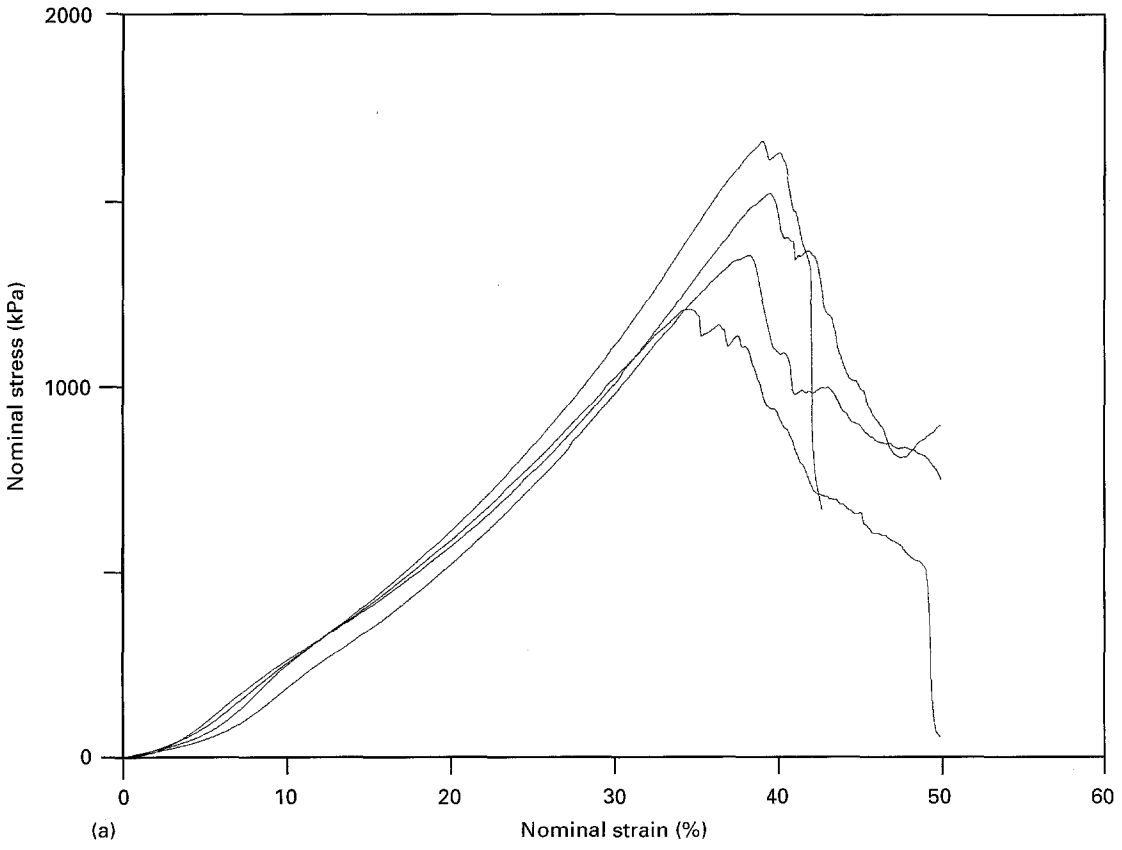
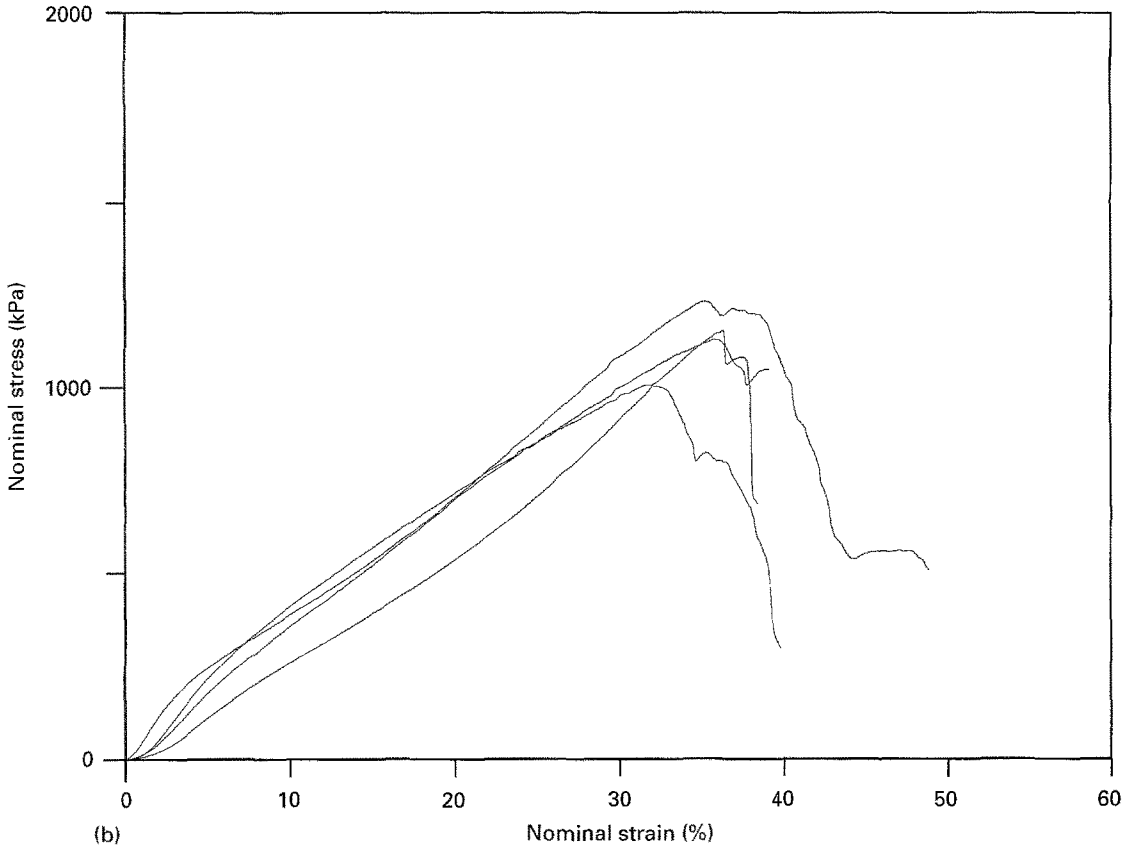


Figure 5 Nominal stress/nominal strain curves for compression of potato tissue cylinders, (cv. Record), showing the effect of turgor. (a) flaccid, (b) fresh, and (c) turgid.



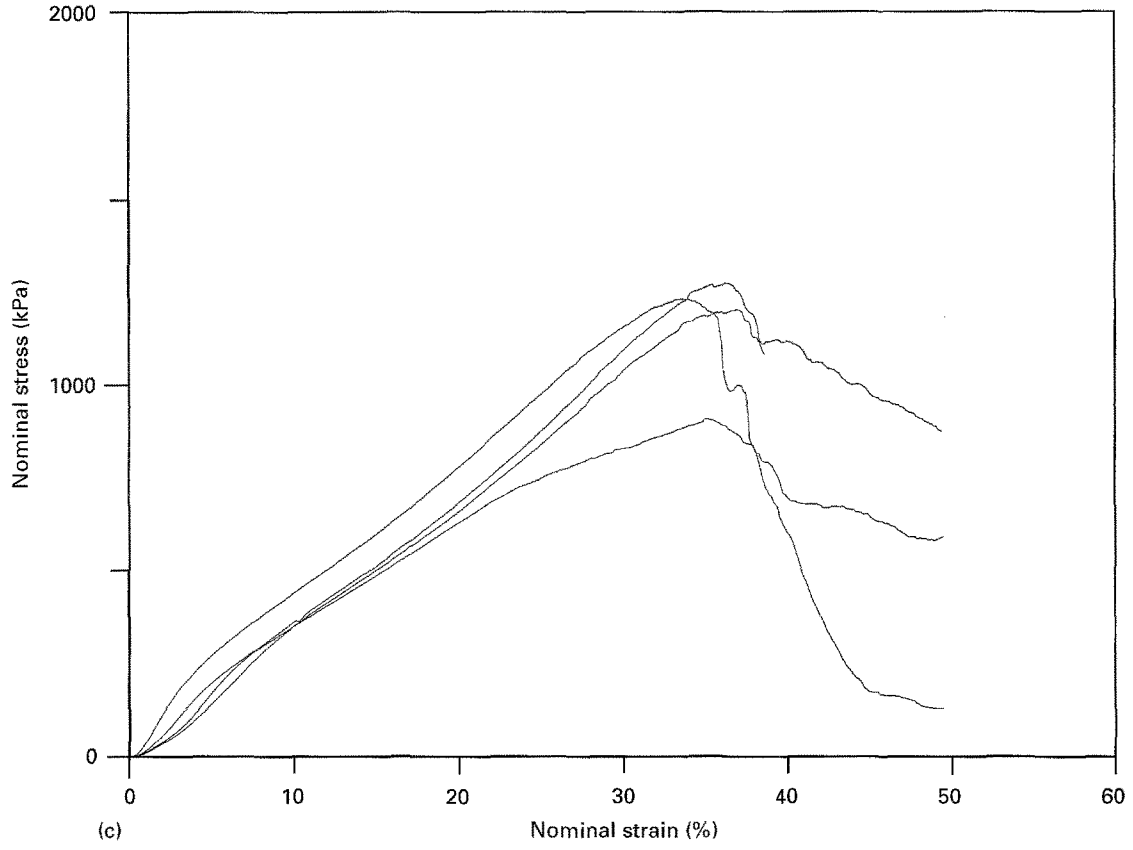


Figure 5 Continued

comparison of sample stiffness, the tangent modulus was estimated at three points on each curve; at the initial point of maximum gradient, at the subsequent point of local minimum gradient, and at the final point of maximum gradient, as shown for a typical curve in Fig. 6, points A, B and C, respectively.

3.1.6. Statistical treatment

Analysis of variance (ANOVA) was carried out to determine the factors associated with significant differences between mean results, for all the tests done. Possible sources of variation considered were tissue turgor alone, variety alone and turgor/variety

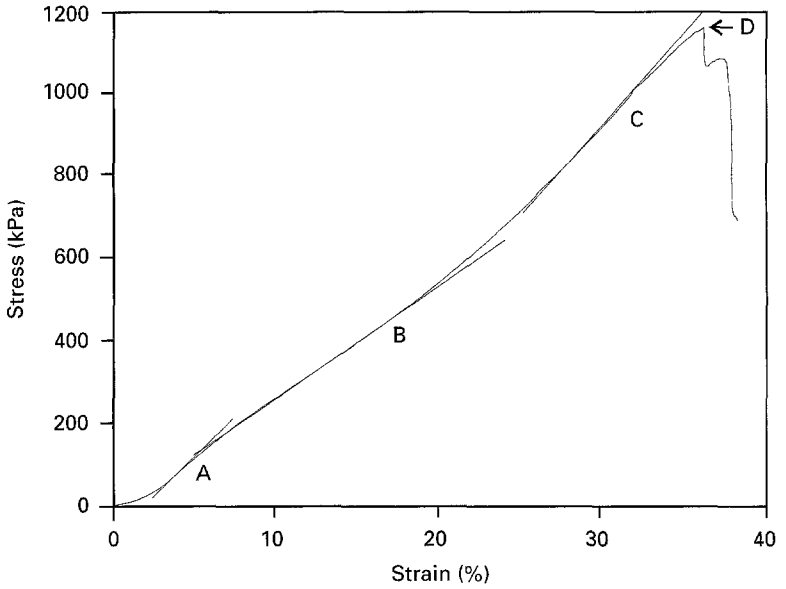


Figure 6 Typical nominal stress/nominal strain curve for fresh potato tuber tissue, showing points A, B and C, at which tangent moduli were estimated, and point D, the stress classified as failure stress.

TABLE II Fracture and cutting tests (King Edward and Record, pooled results). Comparison between flaccid, fresh and turgid samples

	Flaccid	Fresh	Turgid	Standard error of difference of means
Mean work of fracture (wedge-test), R (J m^{-2})	78.0 {6}	34.6 {10}	43.7 {10}	15.4
Mean minimum cutting energy (blade-test), $R_{cut_{min}}$ (J m^{-2})	28.3 {8}	25.0 {8}	37.0 {8}	4.3
Mean maximum cutting energy (blade-test), $R_{cut_{max}}$ (J m^{-2})	32.9 {8}	45.2 {8}	81.8 {8}	9.6

Figures in brackets { } = Number of replicates.

interaction. In no test was a statistically significant difference discovered between the behaviours of varieties King Edward and Record. This being so, one way tables are presented to summarize the effects of tissue turgor on the various mechanical properties of both varieties.

3.1.7. Collated results

The collated results are given in Tables II to V.

TABLE III Fracture and cutting tests (King Edward and Record, pooled results). Comparison between work of fracture and minimum cutting energy

	Mean work of fracture, R(J m^{-2})	Mean minimum cutting energy, $R_{cut_{min}}$ (J m^{-2})	Standard error of difference of means (J m^{-2})
Flaccid	78.0 {6}	28.3 {8}	11.3
Fresh	34.6 {10}	25.0 {8}	11.3
Turgid	43.7 {10}	37.0 {8}	11.3

Figures in brackets { } = Number of replicates.

TABLE IV Ball indentation tests (King Edward and Record, pooled results).

	Flaccid	Fresh	Turgid	Standard error of difference of means
Calculated mean yield stress, σ_y (MPa)	0.194 {24}	0.274 {24}	0.271 {24}	0.012

Figures in brackets { } = Number of replicates.

3.2. Cell pressure tests

Results for the cell pressure tests are given in Table VI.

4. Discussion

4.1. Varietal effects

As mentioned previously, no statistically significant effect of the difference in variety, between cvs. Record and King Edward, could be detected on any of the measured mechanical parameters. This was an unexpected outcome in view of the previously-reported differences in damage characteristics between the two varieties. The limited tests done in this study were

TABLE V Compression tests (King Edward and Record, pooled results)

	Flaccid	Fresh	Turgid	Standard error of difference of means
Mean initial maximum stiffness, E_{init} (MPa)	3.56 {8}	5.49 {8}	5.97 {8}	0.53
Mean subsequent minimum stiffness, E_{cent} (MPa)	2.94 {8}	3.06 {8}	2.77 {8}	0.17
Mean final maximum stiffness, E_{fin} (MPa)	5.40 {8}	3.91 {8}	4.01 {8}	0.31
Mean failure stress, σ_{fail} (MPa)	1.37 {8}	1.16 {8}	1.18 {8}	0.08
Mean failure strain, ε_{fail} (%)	39.14 {8}	34.62 {8}	36.11 {8}	1.53

Figures in brackets { } = Number of replicates.

TABLE VI Results of the limited single cell pressure testing carried out

Variety/ condition	Cell	Turgor pressure (MPa)	Average cell turgor pressure (MPa)
King Edward "Fresh"	(a)	0.225	0.14
	(b)	0.125	
	(c)	0.105	
	(d)	0.100	
	(e)	0.130	
King Edward "Turgid"	(a)	0.550	(0.55)
King Edward "Flaccid"	(a)	0.022	0.03
	(b)	0.036	
Record "Fresh"	–	–	–
Record "Turgid"	(a)	0.450	(0.45)
Record "Flaccid"	(a)	0.060	0.06
	(b)	0.040	
	(c)	0.070	
	(d)	0.059	
	(e)	0.058	
	(f)	0.053	

predominantly aimed at assessing the crack susceptibility of small specimens of tissue under quasi-static conditions. It is possible that the differences in damage characteristics reported to exist between these two varieties relate to bruise formation under high loading rates, rather than to crack susceptibility *per se*. If this were so, then the dissipation of stored mechanical energy via a greater degree of bruising in one variety might serve to retard the onset of brittle fracture in that variety. In any event, no further reference to varietal effects will be made in this discussion.

4.2. Effects of water status

As explained in Section 2.3, the direct measurement of cellular turgor pressure was only successful in producing a limited number of readings. For this reason, results must be taken as indicative only of values within a possible range of turgor pressures for each of the three tissue conditions. Despite these reservations, the results in Table VI show a predictable trend, with a range of turgor pressure values, from 0.03 MPa for tissue in the "flaccid" condition, through 0.14 MPa for "fresh" samples, up to 0.55 MPa for tissue in the "turgid" condition. It is perhaps worth noting that the cells probed in the "flaccid" and "turgid" tissue samples, being on the surface, would undoubtedly have reached equilibrium with the soak solution. Whether this would apply equally to the cells at the centre of the 20 mm cubic samples is open to conjecture. If the centrally-situated cells do not reach equilibrium with the soak solution, mechanical tests on the samples will be likely to underestimate the true effects of turgor pressure change.

4.2.1. Work of fracture

The mean work of fracture, R, was found to be significantly higher in "flaccid" tissue, compared to the values for both "fresh" and "turgid" tissues, between which no statistically significant difference was found.

The work of fracture values obtained in these experiments were generally lower than those reported for similar tissues by previous workers; for example, a value of 389 $J\,m^{-2}$ is quoted for the work of fracture of fresh cv. "Record" tissue as measured in a wedge-fracture test [14]. The precise energy values used to calculate such works of fracture using the so-called "work-area" method are often only vaguely defined, making it difficult to compare one figure with another. It is assumed that such high values were calculated using the energy represented by the total area beneath the force/deflection curve up to fracture, i.e. including energy irreversibly lost in plastic flow and hysteresis. This is clearly not synonymous with the bare energy required to propagate the fracture.

For cleavage cracks in cv. "Sebago" potatoes, produced by compression of whole tubers, a mean work of fracture of 208 $J\,m^{-2}$ was calculated, independent of loading rate over a wide range [15], and even

higher values (1350 J m^{-2}) were reported for the same cultivar by the same authors [16].

It is possible that, by considering successive load/unload cycles as done in our tests, the greater part of any hysteresis losses are discounted from the calculation of work of fracture, resulting in a closer approximation to the true energy associated with the formation of new surfaces, than might be derived through consideration of a steady and continuous wedge penetration. Hence the order of magnitude reduction in work of fracture which we report, compared with previously reported figures.

If there is a weakness in the method used here, it lies in the assumption that, in the absence of crack propagation, the energy recovered by unloading from point "B" would have been equivalent to that recovered by unloading from point "A" (see Fig. 1). The fracture energy values obtained are unfortunately very sensitive to the accuracy of this assumption. In order to test the assumption, representative sets of load/unload cycles from tests on "flaccid", "fresh" and "turgid" tissues were examined. In some tests, no rapid cracking occurred, while in subsequent tests on tissue from the same source, rapid cracking was evident. By calculating works of fracture using various unloading curves, it is possible to estimate the possible errors introduced by the use of the "preceding" unloading curve as a basis for comparison, rather than the use of the "actual" unloading curve. Figs 7–10 show selected results obtained in tests on "flaccid", "turgid" and "fresh" tissue samples; in each case, plot (a) illustrates a test in which a free-running crack did not occur, and plot (b) an immediately subsequent test on comparable tissue, in which a free-running crack did occur. The numbers beneath the unloading curves show the energies recovered in mJ during unloading in each case.

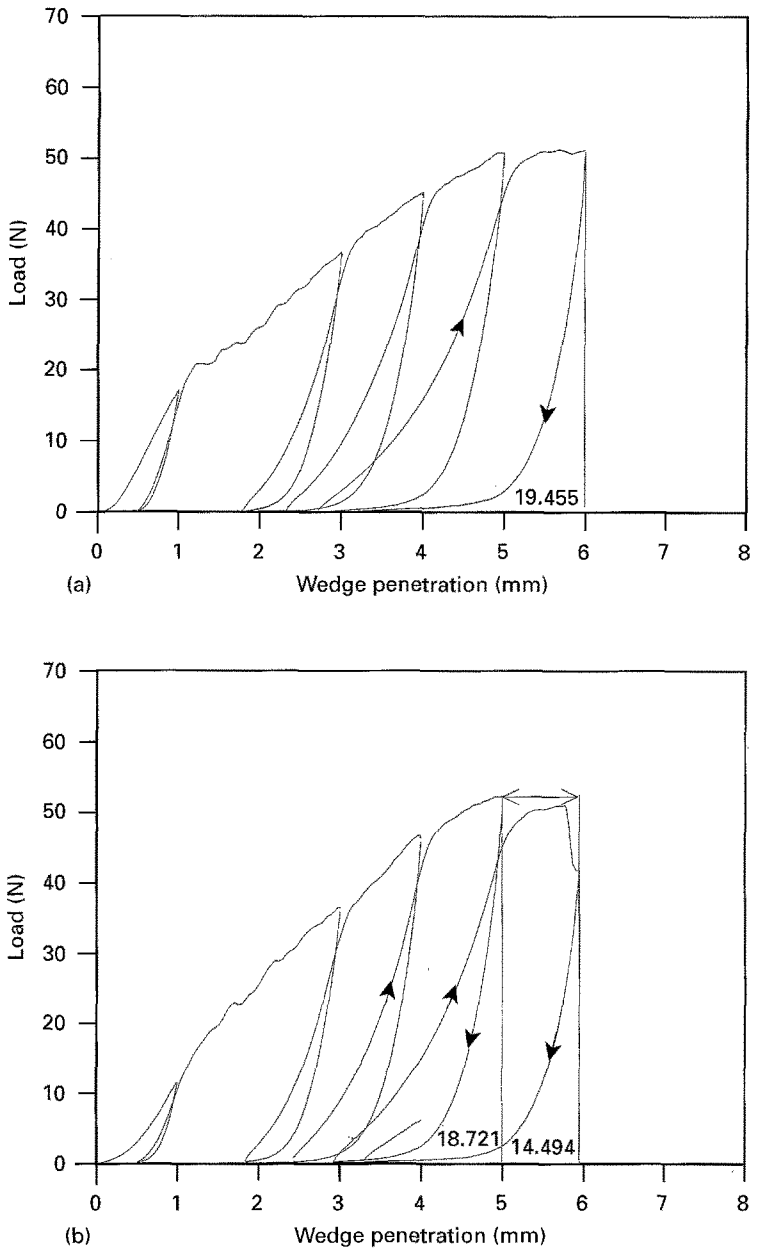


Figure 7 Graphs of load versus wedge penetration for "flaccid" tissue, cv. Record, showing the differences in recovered energy in the absence of cracking, depending on which curve is considered. (a) Test in which free-running crack did not occur. (b) Test in comparable tissue sample in which a free-running crack did occur.

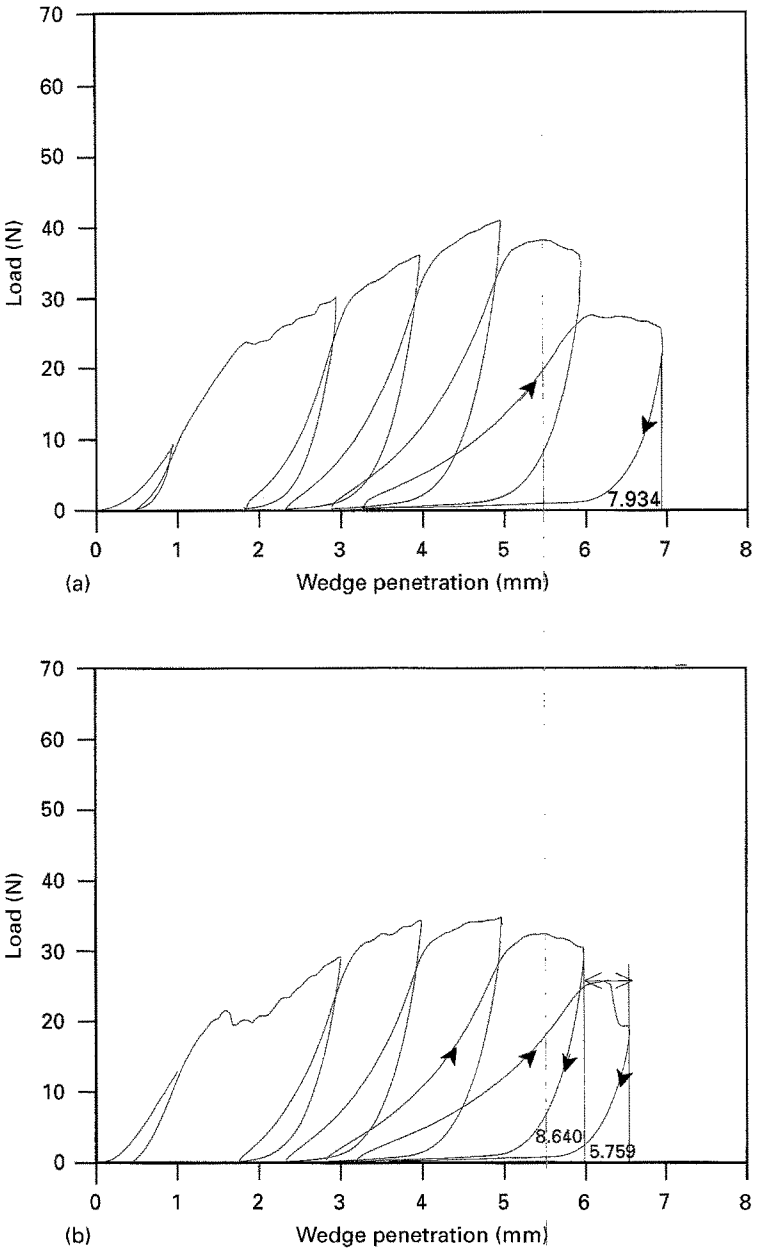


Figure 8 Graphs of load versus wedge penetration for "flaccid" tissue, cv. Record, (further example), showing the differences in recovered energy in the absence of cracking, depending on which curve is considered. (a) Test in which free-running crack did not occur. (b) Test in comparable tissue sample in which a free-running crack did occur.

The essence of the procedure for calculating the work of fracture involves subtracting the "energy recovered after cracking" from a value surmized to be the "energy which would otherwise have been recovered in the absence of a crack", normally based on the unloading portion of the immediately preceding curve from a load equal to that at which the free-running crack commenced in the following cycle. Let us consider the effect of using different available "fracture-free" unloading curves as the basis for calculating work of fracture. Table VII shows work of fracture values calculated using either an immediately-preceding unloading curve, or using an unloading curve from the same cycle in a test on another sample of the same tissue which did not crack.

It can be seen that, depending on the size of the crack being considered, small differences in the unloading curve shapes can introduce substantial differences into the calculated work of fracture. In these cases, errors in the range 8 to 62% could be introduced, depending upon which of the pair of values were taken as the "correct" value. Such considerations are indicative of the difficulties of determining fracture energies generally, compounded by the inherent variability of plant tissues.

4.2.2. Stiffness

The initial maximum stiffness in compression, E_{init}, was significantly lower in "flaccid" tissue than in either the "fresh" or the "turgid" tissues, which were both of comparable higher stiffness. This is not unexpected, and may be explained by the lesser volume of sap within the cells of the "flaccid" tissue, any prestressing of the cell walls having consequently been removed.

Differences in minimum tissue stiffness, E_{cent}, were statistically insignificant at the 3% level.

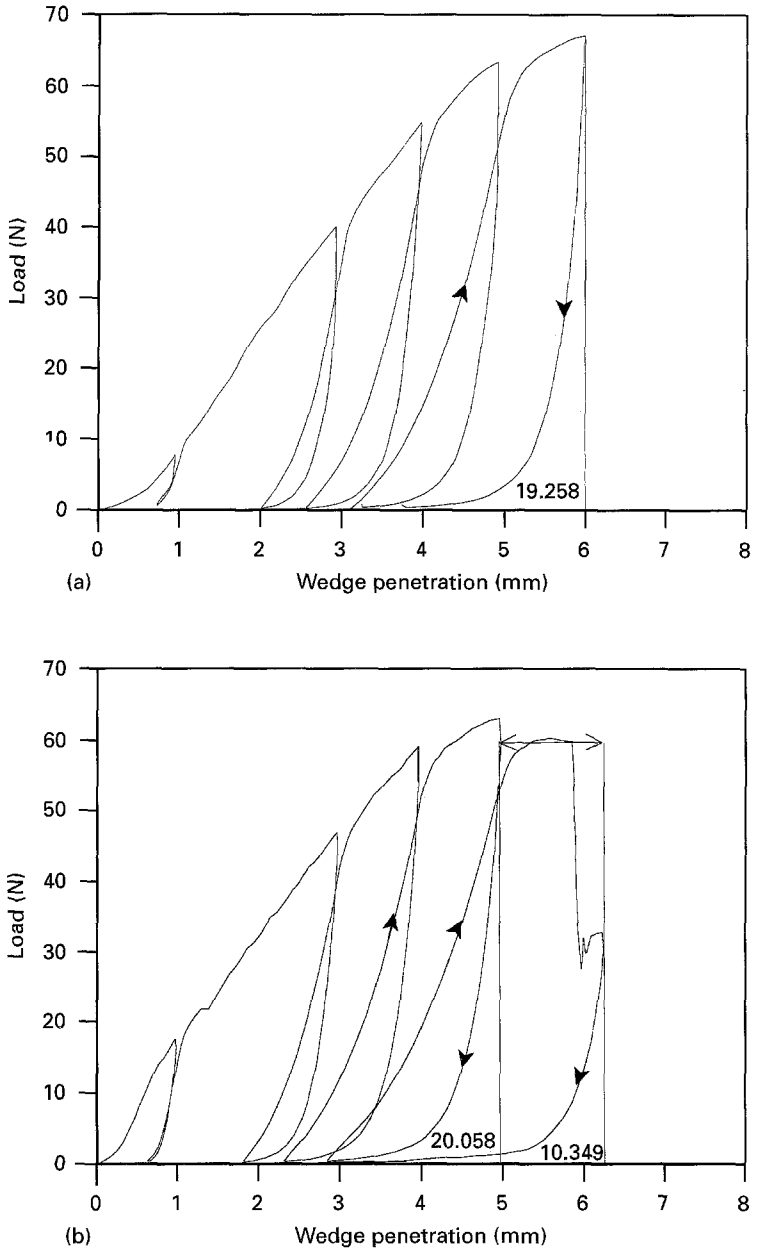


Figure 9 Graphs of load versus wedge penetration for "turgid" tissue, cv. Record, showing the differences in recovered energy in the absence of cracking, depending on which curve is considered. (a) Test in which free-running crack did not occur. (b) Test in comparable tissue sample in which a free-running crack did occur.

Final maximum stiffness, E_{fin}, was significantly higher in the case of "flaccid" tissue samples, compared to values measured for both "fresh" and "turgid" samples. This may appear strange, but can be explained by the fact that all the stiffness measurements are expressed in terms of nominal stress and nominal strain, attributes which relate to the initial sample dimensions, rather than to the instantaneous sample dimensions. Thus, in the case of "flaccid" tissue, the greater flattening of the samples under a given load is the likely cause of the high nominal stiffness values.

4.2.3. Cutting energy

The mean minimum cutting energy, $R_{cut_{min}}$, was also affected by tissue turgor. In this case, the values measured in the "turgid" samples were significantly higher than the values measured in both "flaccid" and "fresh" samples. One possible explanation is increased interaction between the sides of the blade and the surfaces of previously-cut tissue, due to the higher loads imposed on the sides of the blade by lateral deflection of the more rigid turgid tissue. It is difficult to conceive that true friction could operate in the presence of so much lubricating sap. It seems that besides cutting at the sharp edge, however thin the blade, the body of the blade still behaves as would a very thin wedge being driven into the tissue.

Cutting with an infinitely thin blade should provide a measure of the minimum energy required to create new tissue surface, the cutting taking place very close to the edge of the blade and involving the surrounding tissue only minimally. In particular, values of minimum cutting energy, $R_{cut_{min}}$, invariably obtained close to the start of blade penetration, are likely to come

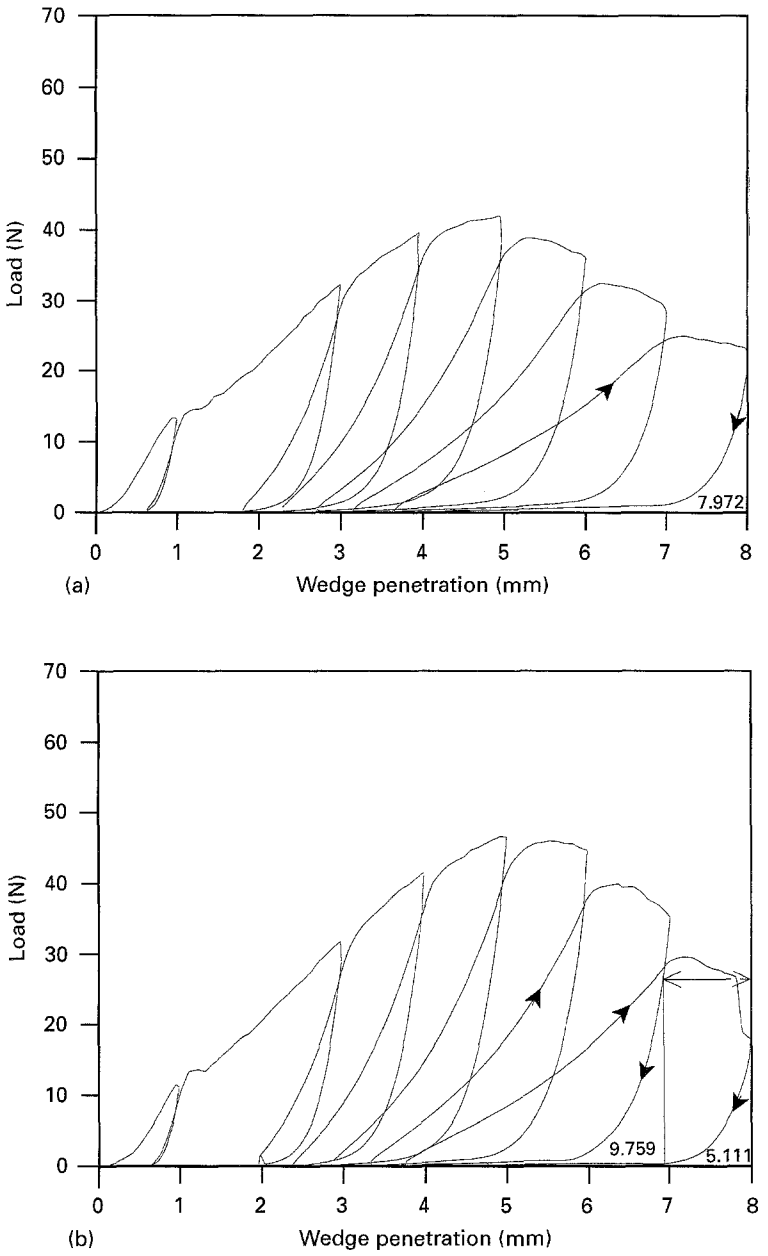


Figure 10 Graphs of load versus wedge penetration for "fresh" tissue, cv. Record, showing the differences in recovered energy in the absence of cracking, depending on which curve is considered. (a) Test in which free-running crack did not occur. (b) Test in comparable tissue sample in which a free-running crack did occur.

closest to reflecting the true energy associated with the rupture of cell walls. In this respect, it is of interest to compare these figures with works of fracture in the same tissues at the same water status. This comparison is shown in Table III. Allowing for the scatter within the measured results, only the "flaccid" tissue condition showed a clearly significant difference between work of fracture and minimum cutting energy. In this case, the minimum cutting energy amounted to somewhat less than half the work of fracture, and suggests that a significant proportion of the fracture energy was dissipated in processes other than cell wall rupture. That work of fracture and minimum cutting energy differed insignificantly in the "fresh" and "turgid" tissues suggests that fracture in these cases proceeded with little loss of energy to processes other than cell wall rupture. In addition, it can be said that the close comparison of the energies measured in the wedge-fracture and blade-cutting tests generally lends credence to the validity of these measurement techniques.

4.2.4. Failure in compression and ball indentation tests

The mean failure stress, σ_{fail}, as measured in the compression tests, was significantly higher for "flaccid" tissue samples, than for either "fresh" or "turgid" samples. This was accompanied by a significantly higher mean failure strain, ε_{fail}, and probably reflects the greater deflections undergone by the initially "emptier" cells of the flaccid tissue before the application of appreciable tensile loading to the cell walls.

The mean yield stress, σ_y, as calculated from the ball indentation test results was found statistically to be significantly lower in the "flaccid" tissue, compared

TABLE VII Possible differences in the calculated work of fracture values due to the variation in shape of comparable unloading curves

Sample condition	Energy recovered after cracking (mJ)	Energy recovered unloading from equivalent load in absence of crack (different sample, same cycle) (mJ)	Energy recovered unloading from equivalent load in absence of crack (same sample, preceding cycle) (mJ)	Calculated fracture energy expended (mJ)
"Flaccid"	14.494	19.455		4.961
	14.494		18.721	4.227
"Flaccid"	5.759	7.934		2.175
	5.759		8.640	2.881
"Fresh"	5.111	7.972		2.861
	5.111		9.759	4.648
"Turgid"	10.349	19.258		8.909
	10.349		20.058	9.709

with the values for both "fresh" and "turgid" tissues, which differed insignificantly from one another. Since the force/penetration gradient was assessed at a given load level in each case, it is hard to ascribe this result to the lesser-filled cells of the flaccid tissue allowing "slack" to be taken up prior to the onset of cell wall extension. Comparing the yield stress values calculated from the ball indentation tests (Table IV), with the mean failure stress values obtained in the compression tests (Table V), it is apparent that the former are smaller than the latter by a factor of between 4.2 and 7.1 times. This difference raises the question of whether or not ball indentation and simple compression tests are measuring an identical yield phenomenon in the potato tissue, as is generally assumed to be the case in metals. It is clear that the macroscopic failure observed in the simple compression tests was invariably "slip" failure of cells in a single plane, whereas the tissue failure observed in the ball indentation tests was far more localized, and not limited to a single plane. If the failure mechanisms are indeed different, this could explain the observed difference in yield/failure stress values.

4.2.5. Critical crack length

If local volume yielding competes with planar brittle fracture as an energy-dissipating mechanism, the applied tensile stress, σ, in Equation 1 may conveniently be replaced by the tissue yield stress, σ_y, namely:

$$L_{c\,min} = \frac{2ER}{\pi\sigma_y^2} \quad (4)$$

The critical crack length L_c has thus been replaced by $L_{c\,min}$, the length of the smallest crack capable of brittle propagation in the tissue, since any value of applied tensile stress σ greater than σ_y will result in the dissipation of stored elastic energy via local volume yielding. Defects smaller than $L_{c\,min}$ will not propagate into plane fractures; failure will occur instead via local yielding.

σ_y values from the ball indentation tests were inserted into Equation 4, together with values for the mean work of fracture, R, and the mean initial maximum stiffness, E_{init}. The results, given in Table VIII, indicate $L_{c\,min}$ values up to 5 mm. Such values are of reasonable order of magnitude when compared to the size of a typical potato tuber, and the not unlikely presence of defects in this size range would be expected to trigger the onset of brittle fracture in tuber tissue.

TABLE VIII Minimum critical crack length values for flaccid, fresh and turgid tissue samples, based on pooled data for King Edward and Record tissue samples

Tissue condition	Stiffness, E_{init} (MPa)	Work of fracture, R ($J\,m^{-2}$)	Yield stress, σ_y (MPa)	Minimum critical crack length, $L_{c\,min}$ (mm)
Flaccid	3.56	78.0	0.194	4.70
Fresh	5.49	34.6	0.274	1.61
Turgid	5.97	43.7	0.271	2.26

Fig. 11 shows values for the critical crack length, L_c, in "flaccid", "fresh" and "turgid" potato tissue samples, under given levels of applied tensile stress in the range 0.075 to 0.5 MPa. Also shown are the points at which local volume yielding takes over from plane fracture. As the applied tensile stress increases, so the critical crack length decreases. However, if the applied tensile stress exceeds a threshold without fracture propagation, local yielding will take place instead. Thus, the behaviour of the tissue is dictated both by the energy balance implicit in the Griffith equation, as well as by the availability of other sinks for stored energy (e.g. local yielding).

As might intuitively be expected, flaccid tissue was found to require a significantly larger flaw for crack propagation under given applied stress, compared to that required to propagate cracks in fresh tissue. Surprisingly, turgid tissue also appeared to require a larger flaw for crack propagation than fresh tissue, and this similarity in the "flaccid" and "turgid" curves compared to the "fresh" curve is puzzling. Flaccid tissue, however, was found to yield locally at lower applied stresses than fresh and turgid tissue. Thus

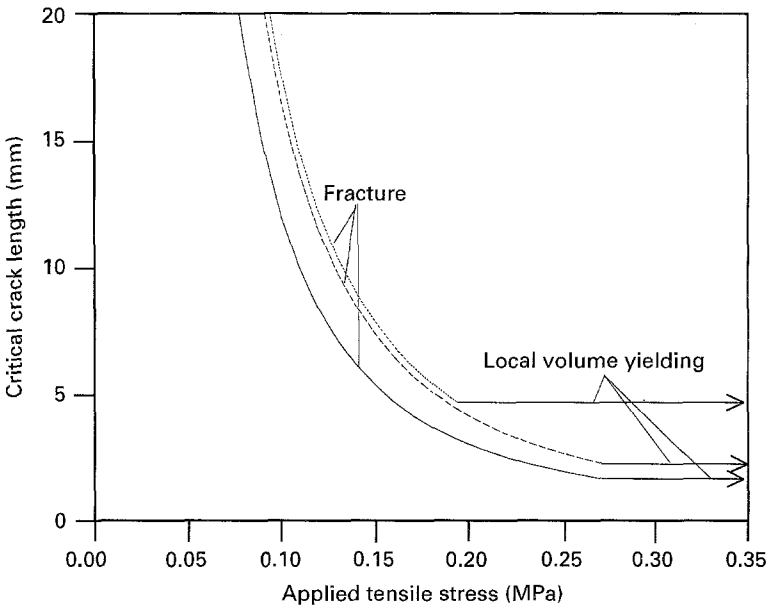


Figure 11 Graph showing the effect of turgor on the calculated critical crack length for fracture propagation under given levels of applied stress. Also shown are the thresholds above which local yielding will predominate over fracture. Key: —— fresh; - - - - - flaccid; —— turgid.

fresh and turgid tissue would fracture in the presence of flaws half the size of the minimum fracture-inducing flaw in flaccid tissue, albeit at higher values of applied tensile stress.

5. Conclusions

(i) No statistically significant differences were found in the mechanical properties of tissue from the two cultivars, "Record" and "King Edward", when tested in various turgor states for work of fracture, work of cutting, compressive stiffness and yield/failure stress.

(ii) Changes in tissue water status were responsible for appreciable changes in mechanical behaviour. In particular, decreasing the turgor pressure to very small values led to a substantial increase in the work of fracture as measured by the wedge-fracture test, accompanied by a decrease in compressive stiffness. The behaviours of "fresh" (turgor pressures in region of 0.1 to 0.225 MPa) and "turgid" (turgor pressures in the region of 0.45 to 0.50 MPa) tissues differed insignificantly with regard to work of fracture, compressive stiffness and failure stress. It would appear that, once cell turgor pressures exceed a certain threshold value, mechanical behaviour is little influenced by further increase of turgor pressure.

(iii) Cutting of turgid tissue was found to require significantly more energy than the cutting of tissue in either the "flaccid" or "fresh" conditions. This may reflect the small but nonetheless finite thickness of the blade used, extra energy being dissipated in the displacement and bending of tissue laterally during penetration.

Comparing work of fracture with cutting energy, no statistically significant difference was found for "fresh" and "turgid" tissue. Although a similar minimum energy was required to cut "flaccid" tissue as was required to cut "fresh" tissue, significantly more energy was required to fracture "flaccid" tissue than to cut it.

(iv) In general, the values of work of fracture measured in these tests were appreciably lower than previously-reported values. The "recovered-energy" experimental method used here may well provide an improved measure of true work of fracture, excluding as it does the effects of energy lost due to hysteresis.

(v) Although ball indentation tests may provide an empirical method by which tissue mechanical properties could be compared, they appear not to relate closely to compressive failure stress, as is generally found to be the case in metals. It is possible that the failure mechanisms involved in the two tests are different. It may be that a different proportionality constant to that used for metals is required for potato tuber tissue.

(vi) Applying the Griffith criterion for crack propagation in brittle materials, it was found that a pre-existing crack of given size in tissue in the "fresh" condition would propagate under a lesser applied tensile stress than would be required to propagate equivalent cracks in both "flaccid" and "turgid" tissues. However, the threshold stress above which local yielding predominated over fracture was substantially lower in flaccid tissue than in either fresh or turgid tissues.

Appendix

"Latin Square" experimental design (Order of testing – read from left to right and top to bottom). Code: A = compression test; B = cutting test; C = indentation test; D = fracture test; R = variety "Record"; K = variety "King Edward".

Day 1: "Fresh" tissue samples

AR	BR	CK	DK
AK	BK	CR	DR
BR	DK	AR	CR
BK	DR	AK	CK
DR	CK	BK	AR
DK	CR	BR	AK
CR	AK	DR	BR
CK	AR	DK	BK

Day 2: "Turgid" tissue samples

BR	AR	CK	DR
BK	AK	CR	DK
CK	DK	BK	AK
CR	DR	BR	AR
DR	BK	AK	CK
DK	BR	AR	CR
AK	CK	DK	BK
AR	CR	DR	BR

Day 3: "Flaccid" tissue samples

CR	DK	AK	BK
CK	DR	AR	BR
BR	AK	DR	CK
BK	AR	DK	CR
CK	DK	AR	BR
CR	DR	AK	BK
BR	AK	DR	CK
BK	AR	DK	CR

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