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Fracture in potatoes and apples

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The application of generalized fracture mechanics to whole potatoes and apples under slow and fast compression is reported. The energy dissipative mechanisms are defined in terms of the hysteresis ratio β, the elastic recovery ratio α, and the fracture toughness. For potatoes, 0.75 of the input energy is dissipated by hysteresis, 0.17 to 0.19 is recovered elastically and the remainder is dissipated by cracking. For apples, 0.30 of the input energy is dissipated by hysteresis, 0.27 to 0.33 is recovered and the remainder is absorbed by cell bursting producing bruising. The fracture toughness of Sebago potato tissue is 208 $\mathrm{J\,m^{-2}}$ for cleavage failures and approximately 770 $\mathrm{J\,m^{-2}}$ for slip failures. The bruise resistance of Granny Smith apples is 0.054 $\mathrm{J\,m^{-3}}$ for slow loading and 0.062 $\mathrm{J\,m^{-3}}$ for impact loading leading to apparent fracture toughnesses of 5.4 $\mathrm{J\,m^{-2}}$ and 6.2 $\mathrm{J\,m^{-2}}$, respectively. It is estimated that only approximately 0.03 cells within the bruised region are fractured. The hysteresis ratio β, the recovery ratio α and the fracture toughness are important properties of these two crops and enable the interpretation of distribution of energy inputs to produce during processes, handling and transport.

1. Introduction

An understanding of mechanical failure in fruit and vegetables is essential to the reduction of damage and energy consumption in processing, handling and transport operations in horticultural distribution. Mohsenin [1] states that one of the by-products of mechanization in production and handling of agricultural products has been mechanical damage to the crop. Fruit and vegetables are particularly sensitive to loads imposed during handling. O'Brien *et al.* [2] found that the progressive loss or damage of peaches, apricots and tomatoes was approximately 50, 50 and 60%, respectively, between harvesting and processing. Bourne [3] shows that texture or eating quality is also strongly influenced by the mechanical properties of the tissue. It is apparent that the mechanial response of fruit and vegetable tissue to applied loads is of major concern.

Holt and Schoorl [4] have proposed that mechanical failure in fruit and vegetables can be classified as cleavage, slip or bruising. Cleavage, that is cracking and splitting, is a normal stress phenomenon and slip, where failure occurs along planes at 45° to the direction of loading, is a shear stress phenomenon. Bruising occurs in regions where individual parenchyma cells are distorted and eventually burst so that, on the bulk material scale, bruising is also a shear phenomenon occurring when the difference in normal stress reaches some limit. The walls of individual cells may, however, rupture by splitting or slip. For both cleavage and shear failure, it has been shown that the amount of damage is directly related to the amount of energy absorbed, [5–8]. Thus the energy dissipative mechanisms up to and during failure in horticultural produce may provide the key to the control and management of damage.

Andrews [9] suggests that the term "fracture" can be used to embrace a wide variety of failure phenomena in materials under stress. Andrews [10], Andrews and Billington [11] and Andrews

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and Fukahori [12] have put forward a generalized theory of fracture mechanics which gives fracture criteria for solids in general without limitations as to their linearity, elastic behaviour or infinitesimal strain. Andrews [9] suggests that the theory represents the best available starting point for the consideration of fracture and failure in biological systems. Jeronimidis [13] and Gordon and Jeronimidis [14] have also investigated the fracture behaviour of biological materials and composities and have derived values for the work of fracture of certain types of wood. Vincent [15] has studied the mechanical design of grass and estimates values for the specific work of fracture for perennial rye-grass leaves. These authors demonstrate the applicability of fracture mechanics to failure phenomena in biological materials.

Andrews [9] describes the development of generalized fracture mechanics and shows how the apparent energy required to form unit area of crack surface equals the actual energy so required multiplied by a "loss function", Φ, which varies from unity for perfectly elastic solids to infinity for solids with a sufficiently large mechanical hysteresis. The critical energy release rate, J, is thus given by

$$J = J_0\Phi$$

where J_0 = actual energy required to form unit area of crack. The loss function Φ depends on the hysteresis ratio, β, and hence on any environmental condition which affects β, for example, temperature and strain rate. When $\beta = 0$, the only energy required to propagate a crack is that needed to form the new surfaces, namely J_0. As β increases, the energy required to form new surfaces rises without limit. The hysteresis ratio, β, thus controls the proportion of the energy input which is available to produce new surfaces, that is to produce damage by splitting or cracking, and conversely the amount of energy which is dissipated by other mechanisms such as internal friction, that is hysteresis losses.

This paper examines the mechanical properties of potatoes and apples under slow and fast compression. For both crops energy dissipative mechanisms are described and the modes of failure defined. In potatoes, cracking by slip and cleavage occurs; in apples bruising by cell bursting is the mode of failure. Cracking is a fracture phenomenon and it will be argued that bruising, at the cellular level, is also a fracture phenomenon. The energy dissipative mechanisms are described by three parameters, the hysteresis ratio, the recovery ratio (related to the coefficient of restitution) and the fracture toughness.

2. Experimental procedure

Whole potatoes and apples were subjected to slow and dynamic compression in April, 1982. An Instron Universal Tester, Model 1122, was used for the slow compression tests. Dynamic tests were carried out by impacting whole specimens against a solid concrete block. Tests were performed on Sebago potatoes and Granny Smith apples.

2.1. Potatoes

For quasi-static tests, the tuber was mounted between flat plates and compressed at constant speeds, 20, 50 and 100 mm min^{-1}. The tubers were ellipsoidal in shape and positioned between the loading plates with the long axis horizontal. The potatoes were freshly harvested and specimens were selected for evenness of shape and size and were free from blemishes. The mass of individual tubers ranged between 0.18 to 0.24 kg. They were selected in matched pairs. One tuber was compressed until cracking occurred, indicated by a sudden drop in load, frequently accompanied by a loud noise. The platen was immediately halted and then reversed at the loading speed. The second tuber was compressed to about 75% of the failure load of the first tuber, the platen halted and reversed as before. This second tuber was generally undamaged. Force and deflection were recorded on a chart and energies were calculated from the areas under the force–deflection curve.

Impact tests of potatoes were carried out using a pendulum. Each tuber was suspended on a thin cord attached with a cuphook and allowed to swing through an arc from a height of approximately 1.5 to 2 m to impact upon a smooth, vertical concrete surface. Again matched pairs were tested, the first tuber dropped from a height which caused cracking and the second dropped from a somewhat lower height. The onset or avoidance of cracking was more difficult to predict than in the slow compression tests but this was overcome by using sufficient replicates. The drop height and rebound heights were recorded and the input and recovered energies were calculated from height and mass.

In both slowly compressed and impacted

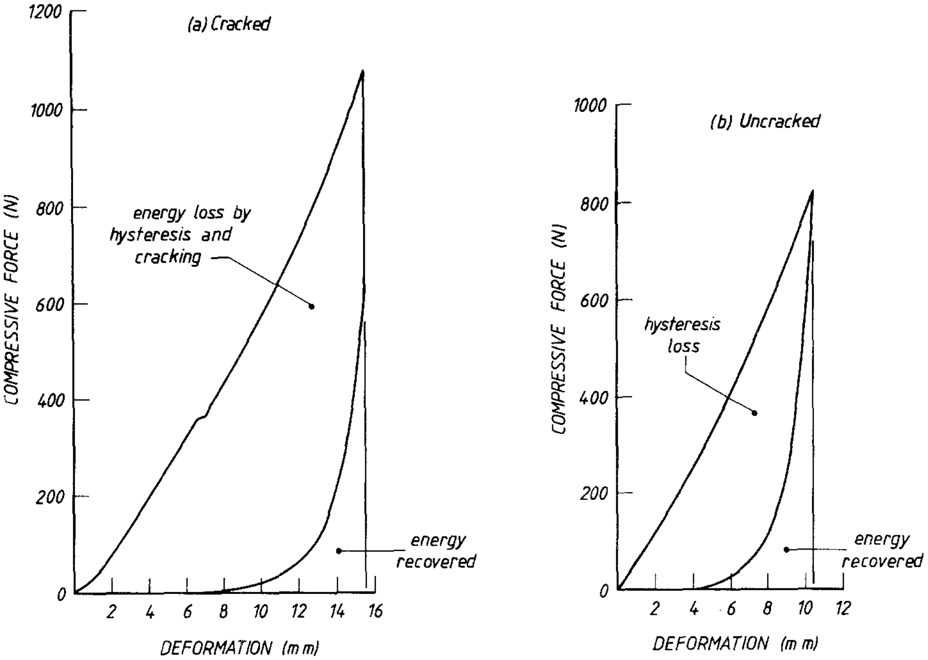

Figure 1 Typical force–deformation curves for uncracked and cracked Sebago potato tubers under quasi-static compression.

potatoes, the crack area was measured by allowing the tested tuber to stand for 24 h, cutting the specimen open and recording the dimensions of the dried crack surface. All specimens were cut open along two planes at right angles and carefully inspected. For 20, 50, 100 mm min^{-1} and impact tests (approximately 5.4 and 6.3 m sec^{-1}) the number of replicates for cracked specimens was 10, 8, 9 and 14, respectively.

2.2. Apples

For slow compression tests on apples, whole pieces of fruit were compressed between two flat plates on the Instron at 20, 50 and 100 mm min^{-1}. The fruit was harvested about 1 month before testing and held at 1° C until required. The mass varied from approximately 0.15 to 0.17 kg and the average diameter was about 70 to 72 mm. Specimens were selected for uniformity of shape and size and freedom from blemish. Each specimen was positioned in the Instron with the flower-to-stalk axis horizontal and compressed by about 8 to 10 mm. Force and deformation were recorded on chart and energies calculated from the areas under the force–deformation curve.

For apples a pendulum impact test similar to that described for potatoes was used with a constant drop height of 0.5 m. The cord was attached to each apple by a cuphook inserted at the stalk end and the apple impacted on the cheek. The rebound height was measured and input and recovered energy were calculated from height and mass.

After both quasi-static compression and impact testing, the apples were allowed to stand for 24 h. A wedge section was taken out of the bruised regions to reveal the width and depth of the bruised tissue. The bruised volume was calculated from width and depth measurements as described by Holt and Schoorl [5, 16]. In the quasi-static tests the total volume of the two bruises, one on the bottom of the apple and the other on top, was recorded. For 20, 50 and 100 mm min^{-1} compression and the impact tests, approximately 3.1 m sec^{-1}, 10, 5, 5 and 10 replicates were used, respectively.

3. Results

3.1. Potatoes

Typical force–deformation curves for quasi-static compression of whole potatoes for cracked and uncracked specimens are shown in Figs. 1a and b. On a rising load the curve is concave upwards. For uncracked specimens, Fig. 1b, the unloading curve is similar in shape to but below the loading curve, producing a hysteresis loop. The hysteresis ratio,

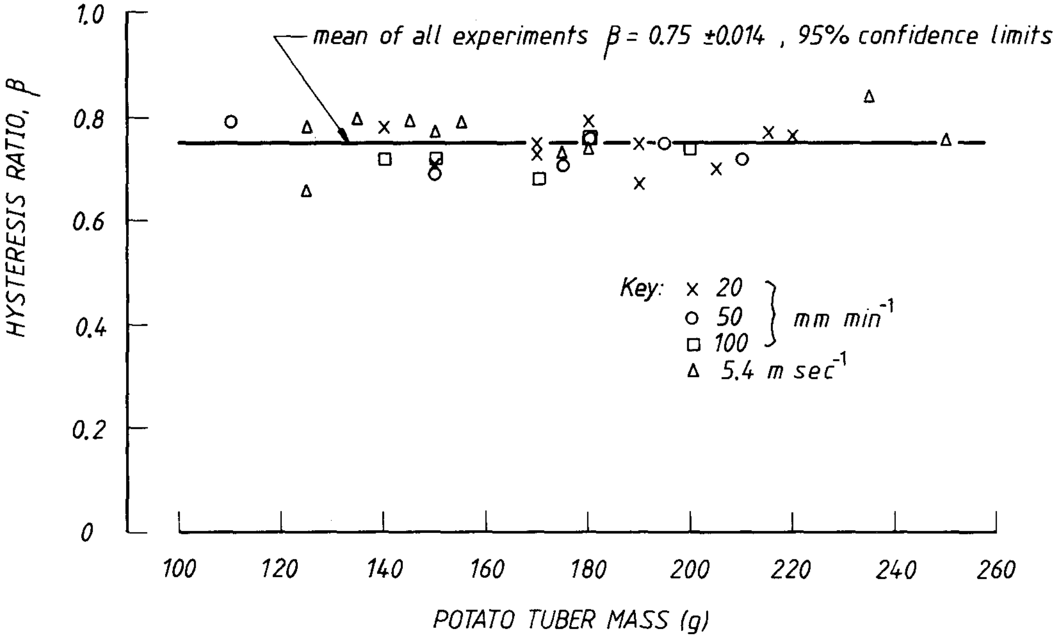

Figure 2 Hysteresis ratio β against potato tuber mass for uncracked specimens under slow and fast loading rates.

β, can be defined as the ratio of the energy dissipated to the total energy input, that is, the ratio of the hysteresis loop area to the total area under the loading curve. For impacted specimens the hysteresis ratio can be defined as

$$\beta = \frac{mg(h_\mathrm{d} - h_\mathrm{r})}{mg\,h_\mathrm{d}} = \frac{h_\mathrm{d} - h_\mathrm{r}}{h_\mathrm{d}}$$

where m is the mass of tuber, g is the gravitational constant, h_d is the drop height and h_r is the rebound height. The hysteresis ratio is plotted against tuber mass for both quasi-static and impact loading in Fig. 2. Total energy inputs for slow loading rates averaged 6.6 J for cracked specimens and 4.0 J for uncracked specimens and for impact 3.0 and 2.5 J, respectively. Full results are given in Table I.

TABLE I Results of quasi-static and impact compression on potatoes

		Loading rate			
		20 mm min⁻¹	50 mm min⁻¹	100 mm min⁻¹	5.4 m sec⁻¹ uncracked 6.3 m sec⁻¹ cracked
Energy input (J)	cracked	6.55	6.92	6.2	2.99
	uncracked	4.2	4	3.87	2.45
External cracks	number	3	4	6	14
	total area ($m^2 \times 10^{-3}$)	8.77	13.72	18.36	20.34
Internal cracks	number	7	4	3	2
	total area ($m^2 \times 10^{-3}$)	7.88	3.00	4.01	0.92
Hysteresis ratio, β	Mean		0.75		
	SD*		0.04		
Recovery ratio, α (cracked specimens)	external	0.16	0.13	0.16	0.18
	internal	0.18	0.19	0.18	
Recovery ratio, α	Mean		0.17 (ext)	0.19 (int)	
	SD		0.05	0.04	

*SD – standard deviation.

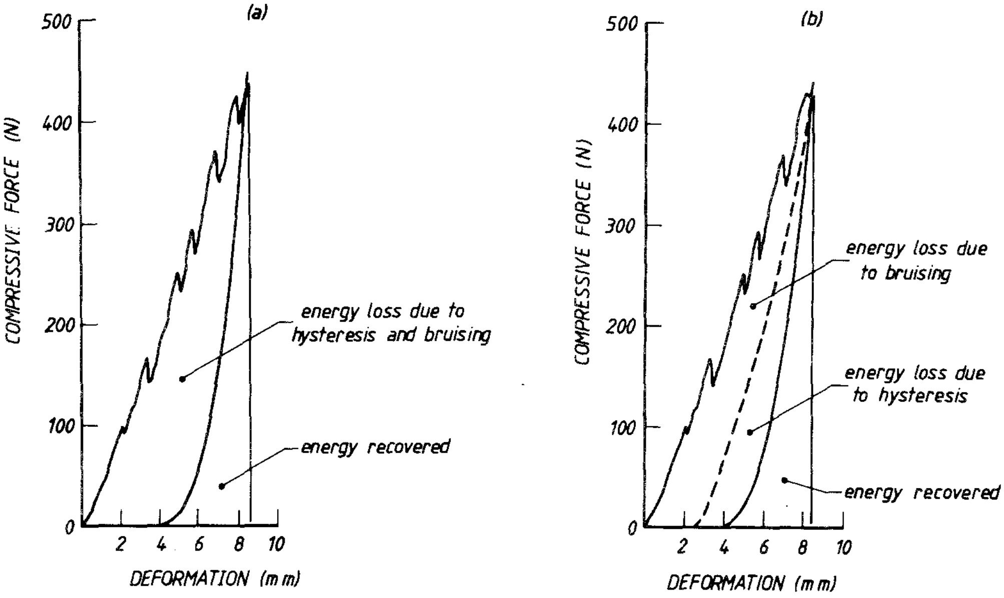

Figure 3 Force–deformation curves for quasi-static compression of Granny Smith Apples.

When specimens are cracked under slow loading the unloading curve falls rapidly and the energy recovered elastically is reduced, as shown in Fig. 1a. The hysteresis loop now includes energy dissipated by cracking as well as energy dissipated by the other mechanisms operating in the uncracked specimens. In impacted cracked tubers the extra energy dissipated results in lower rebound heights. The size, number and location of cracks under all loading conditions is recorded in Table I. Considering the tuber to be loaded at the poles for slow compression, and at one pole for impacts, one sort of crack occurred across the equator, the plane of the crack in the direction of the loading. Another type of crack occurred inside the tuber at or near the centre, with the plane of the crack at 45° to the loading direction. These two types of cracks are termed external and internal, respectively, in Table I. With larger internal cracks, the orientation of the crack surface changed from 45° to parallel to the loading direction as the crack extended away from the centre. Furthermore, internal fracture surfaces were always accompanied by a greyish discoloured region extending into the surrounding tissue. No such discolouration was seen in any uncracked specimens.

The ratio, α, of the energy elastically recovered to the total energy input for both internal and external cracking is given in Table I for all loading rates, together with the mean and standard deviation for all internal and external cracking. There is no α value for internal cracking for impact loading since external cracking was the dominating mode and internal cracks occurred in only 2 out of 14 cases, and in these cases the area of the internal cracks was a small proportion of the total. Crack areas and energy input for external and internal cracks for all loading rates are given in Table II.

3.2. Apples

A representative force–deformation curve for quasi-static compression of whole apples is shown in Fig 3a. The most noticeable characteristic is the sudden the continual discontinuities in the loading curve. This behaviour was accompanied by distinct popping noises. The unloading part of the curve is smooth and concave upwards. The energy recovered is again represented by the area under the unloading curve and the total energy dissipated is proportional to the area contained by the loading and unloading curves. The energy dissipated is made up of energy absorbed by cell bursting, i.e. bruising and energy dissipated by other mechanisms. Fig. 3b is an attempt to separate the energy absorbed in bruising from the total energy dissipated to give an estimate of the hysteresis ratio. The dashed line in Fig. 3b is constructed by drawing the envelope of lines parallel to the rising portions of the loading curve between the discontinuities. The curve is begun at the peak

TABLE II Energy inputs and crack areas for quasi-static and impact compression of potatoes [E = energy in (J), A = crack area ($m^2 \times 10^{-3}$)]

External cracks								Internal cracks							
Loading rate								Loading rate							
20 mm min^{-1}		50 mm min^{-1}		100 mm min^{-1}		6.3 m sec^{-1}		20 mm min^{-1}		50 mm min^{-1}		100 mm min^{-1}		6.3 m sec^{-1}	
E	*A*	*E*	*A*	*E*	*A*	*E*	*A*	*E*	*A*	*E*	*A*	*E*	*A*	*E*	*A*
3.03	2.5	7.68	3.7	7.73	5.3	3.24	0.59	5.78	1.11	7.44	1.46	8.94	1.41		
6.96	2.7	10.06	4.39	4.41	2.48	4.29	4.28	5.18	3.84	5.31	0.47	5.53	1.51		
8.71	3.7	8.63	2.72	6.63	2.67	3.16	0.47	5.86	0.31	4.16	0.79	5.72	1.09		
		9.65	2.91	7.66	3.37	2.94	0.59	1.03	1.02	5.13	0.28				
				2.62	2.83	3.53	1.41	5.73	0.38						
				6.51	1.71	3.73	1.63	4.3	0.96						
						2.55	1.16	0.87	0.26						
						3.24	3.02								
						3.14	0.84								
						3.14	2.69								
						1.99	0.75								
						1.84	1.69								
						1.91	0.76								
						2.55	1.38								

TABLE III Results of quasi-static and impact compression of apples

		Loading rate			
		20 mm min^{-1}	50 mm min^{-1}	100 mm min^{-1}	3.1 m sec^{-1}
Energy input (J)	Mean	1.46	2.54	1.8	0.78
	SD	0.14	0.22	0.16	0.06
Hysteresis ratio, β	Mean	0.29	0.30	0.30	
	SD	0.03	0.05	0.06	
Hysteresis ratio, β, slow compression	Mean	0.30	0.30	0.30	0.30
	SD	0.04	0.04	0.04	0.04
Recovery ratio, α	Mean	0.35	0.30	0.34	0.27
	SD	0.04	0.03	0.03	0.02
Recovery ratio, α (combined)	Mean	0.33	0.33	0.33	0.27
	SD	0.04	0.04	0.04	0.02
Bruise volume (ml)	Mean	9.90	17.40	12.62	5.45
	SD	2.15	3.11	1.18	0.77

force and drawn down to the base line. The dashed curve thus approximates what would have been the response of the apple had not cell bursting occurred. The energy dissipated by hysteresis mechanisms is proportional to the area enclosed by the dashed curve and the unloading curve. The energy dissipated by bruising is proportional to the area between the loading curve and the dashed curve. The hysteresis ratio can now be defined as the ratio of the area between the dashed curve and the unloading curve and the total area below the loading curve. Values determined in this manner for all quasi-static tests are shown statistically summarized in Table III. Since there was no force–deformation record for the impact texts the hysteresis ratio, β, could not be calculated. Energy inputs and the ratio, α, of energy recovered to energy input for all loading rates are also summarized in Table III.

In apples, the extent of damage can be measured by the volume of bruised tissue. After slow compression in the Instron there are two bruised regions involved and after impact tests there is a single contact region. Total bruise volumes are given in Table III. During bruise volume measurements, when each bruise was sectioned, it was observed that the bruised region in impact tests was uniformly damaged whereas bruises resulting from slow compression testing exhibited distinct bands of broken tissue. Between these bands, which were curved surfaces, the tissue was relatively undamaged. The whole bruised region was discoloured but the unbroken cells could be discerned. This effect is shown in Fig. 4.

4. Discussion

Figs. 1 and 3 are examples of different failure modes in biological materials. Fig. 1 shows the response of potatoes to applied loads which result in failure by cracking. Fig. 3 shows what happens when continuous tissue failure occurs, in this case for apples, resulting in bruising. In both cases, the energy inputs are dissipated by several different mechanisms and only part of the input energy is absorbed by cracking or bruising.

4.1. Mechanical failure in potatoes

When whole potatoes are loaded in compression, there are three different energy dissipative mechanisms operating. If loading is halted before cracking occurs, all the input energy is either recovered elastically or lost by hysteresis. When sepcimens crack, energy is also dissipated with the formation of new crack surfaces. Most of the input energy is lost by hysteresis as shown in Fig. 2 where the hysteresis ratio $\beta = 0.75$. The hysteresis ratio is independent of tuber mass and loading rate. No apparent damage results from the absorption of 75% of the input energy. The cells are filled with starch granules which may also be effective in dissipating energy by internal friction when gross distortion of the bulk tissue occurs.

Figure 4 Sections of bruised regions resulting from quasi-static (left) and impact (right) compression of whole apples (70 to 72 mm diameter) showing layered cell bursting.

All of the energy stored elastically, that is 25% of the input energy, is recovered when the tuber remains uncracked. When the tuber cracks externally, 17% is recovered elastically and 8% is consumed in cracking. When internal cracking occurs, 19% of the input energy is recovered and 6% is lost in cracking. The ratio of energy recovered to energy input for cracked specimens, α, is thus approximately constant at 0.17 for external cracking and 0.19 for internal cracking. The mechanism operating here is probably the elastic recovery of stretched cell walls. A coefficient of restitution, e can be defined in terms of the recovery ratio, namely $e = \alpha^{1/2}$.

When cracking does occur under both quasi-static and impact loading of whole potatoes there are two failure modes as evidenced by the different orientation of fracture surfaces for internal and external cracking. Internal cracking occurred on planes at 45° to the direction of loading in the centre of the tuber and is hence a slip failure. There was no tissue damage apparent either side of the slip plane although after 24 h the crack surfaces were surrounded by grey discolouration. This centre greying has been described previously as black heart or black spot and is caused by a deficiency of oxygen in the interior of the potatoes [1]. The results here show that it is induced by cracking since uncracked tubers showed no sign of discolouration after compression or impact. Cracking also occurred around the periphery of the tuber and the crack surfaces were parallel to the direction of loading. These external cracks are the result of induced tensile hoop stresses and are thus cleavage failures. The compressed tubers failed by both slip and cleavage. Some tubers clearly showed the transition between slip and cleavage on the same crack surface as the crack extended from the centre towards the exterior. The crack surface changed from a 45° plane by screwing into a plane parallel to the load.

A qualitative description of the stress state and modes of failure for potato tissue in the two extreme positions, i.e. the centre and the periphery of the tuber, is given in Fig. 5. The Mohr's circle description of the stress state is shown for

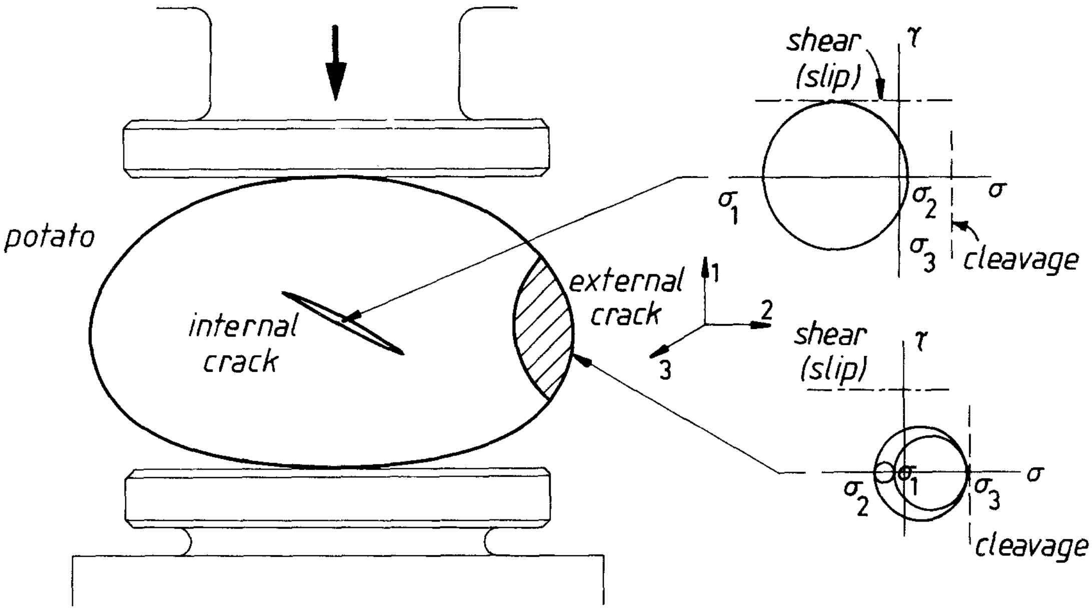

Figure 5 Qualitative representation of failure conditions in potatoes under compression showing slip and cleavage strength limits superimposed on Mohr's circles.

these two positions. At the centre, σ_1 in the direction of loading is large and compressive and σ_2, σ_3 are small, tensile and approximately equal. Mohr's circles are centred to the left of the shear stress axis. On the periphery, maintaining the same nomenclature, σ_1 is now much smaller although perhaps still compressive, σ_2 in the radial direction is compressive and small but σ_3 around the periphery is now tensile. The Mohr's circles are smaller in diameter, i.e. the maximum shear stress is smaller but the circles have moved to the right along the normal stress axis. It may further be postulated that there will be limiting values of stress on both the shear and normal stress axis corresponding to the current slip and cleavage strength of potato tissue. These limiting values are indicated in Fig. 5. On a rising load, material in the centre is subjected to shear stresses which reach a limiting value and slip along 45° planes occurs. There is no tendency towards cleavage since no tensile stresses exist. On the periphery, on the other hand, smaller shear stresses develop but the maximum normal stress is tensile and eventually reaches a limiting value, the cleavage strength of the material. This cleavage failure occurs before the shear stresses are large enough to cause slip failure, as indicated by the smaller Mohr's circles.

The relative occurrence of slip and cleavage failure is strain rate dependent. At the slowest loading rate, 20 mm min^{-1}, the areas of external and internal cracks for all specimens are about the same, although more internal cracks were found. As the loading rate increased the number and area of internal cracks dropped until for impact tests only 2 internal cracks were observed in 14 specimens representing 4% of the total crack area.

The energy absorbed by cracking for both slip (internal cracks) and cleavage (external cracks) failures is given by

$$E_{\text{abs}} = (1 - \beta - \alpha) E_{\text{in}}$$

where E_{abs} is the energy absorbed in cracking, β is the hysteresis ratio, α is the recovery ratio and E_{in} is the total energy input. The energy absorbed per unit area of crack is a measure of fracture toughness and values calculated from data in Tables I and II for various loading rates are given in Table IV. The crack area used in these calculations includes both surfaces of each crack.

Considering the very large range of loading rates, from 20 mm min^{-1} to 6.3 m sec^{-1}, the fracture toughness of potato tissue failing by cleavage can be said to be independent of the loading rate. The overall mean and standard deviation for all external cracks for all loading rates, is 208 Jm^{-2} and 112, respectively. The energy required to produce slip, on the other hand, is very much higher than this at slow loading rates (770 Jm^{-2}) and decreases as loading rates increase. The loading

TABLE IV Fracture toughness for external and internal cracks in potatoes (Jm^{-2})

		Loading rate			
		20 mm min^{-1}	50 mm min^{-1}	100 mm min^{-1}	6.3 m sec^{-1}
External cracks (cleavage)	Mean	167	199	193	225
	SD	62	38	90	142
Internal cracks (slip)	Mean	770	598	305	–
	SD	666	371	79	–

rate effect may be due to the changeover from slip to cleavage failures shown in Tables I and II. This view is supported by observations of the 45° slip plane changing direction as the crack progressed to the outside. The fact that cleavage cracks appear further towards the centre at higher loading rates may be due to an increase in slip strength with strain rate. Referring to the Mohr's Circles in Fig. 5, the shear strength boundary moves up the shear stress axis making it more likely, as the load is increased, that a cleavage boundary is met on the normal stress axis.

4.2. Mechanical failure in apples

When whole apples are loaded in quasi-static compression there are, as for potatoes under compression, three different energy dissipative mechanisms operating. Some energy is stored elastically and recovered on the release of the load. Some energy is dissipated in hysteresis. Unlike potatoes, however, which crack when the stored energy reaches sufficiently high levels, apples fail continuously by bruising and energy is dissipated by this mechanism. Fig. 3 shows the relative amounts of energy accounted for by hysteresis, recovery and bruising for slow loading rates. Similar mechanisms appear to operate under impact loading since the failure mode remains the same.

Table III shows that the hysteresis ratio, β, is the same for the three slow loading rates at about 0.3. Since there was no direct calculation of the hysteresis ratio for impact conditions, this value will be assumed for later energy balance calculations. These results show that 30% of the input is dissipated by mechanisms other than bruising and elastic recovery. Apple tissue is made up of liquid-filled parenchyma cells and it may be postulated that the energy absorbed as hysteresis is dissipated in the cell walls. The liquid within each cell is unlikely to absorb much energy as the cell is distorted and this may account for the lower β in apples compared to potato tissue. The proportion of input energy recovered in apples is 0.33 for slow loading and 0.27 for impact. This may be compared with 0.24 for uncracked potatoes and 0.17 to 0.19 for cracked specimens. Elastic recovery in apples is probably due to the recovery of elastic deformation in the cell walls.

Under all the experimental loading conditions, apple tissue failed by bruising at the contact regions. Bruising is the result of cell bursting as shown by electron micrographs of damaged apple tissue [17]. Holt and Schoorl [5] have described the shape of the bruised region and shown that the boundaries correspond with surfaces of constant shear stress found for a sphere of photoelastic material under compression. Cell bursting occurs by a fracture of the cell walls as the cell itself is distorted from a nearly spherical shape to an ellipsoidal shape. Since the cell contents are relatively incompressible, this distortion of the cell results in stretching of the cell wall, leading to final fracture. It seems reasonable then to describe bruising as a shear phenomenon in the bulk material since maximum distortion will occur on surfaces of maximum shear stress. On this basis, Fig. 6 shows qualitatively the stress conditions at the boundary of the bruised regions together with the strength limits. At the bruise boundary, σ_1 is compressive and large and σ_2 and σ_3 are probably tensile along the centre line changing to compression away from that line, but in either case will be small. The Mohr's circles, $\sigma_1\sigma_2$ and $\sigma_1\sigma_3$ are approximately the same large diameter and as load increases they reach the current shear strength limit. On the periphery, σ_1 has dropped to almost zero, although still compressive, σ_2 is compressive and small and the hoop stress σ_3 is also small since very little distortion of the whole apple occurs because of the continuous bruising. The Mohr's circles are small and do not reach either the cleavage or shear strength limits.

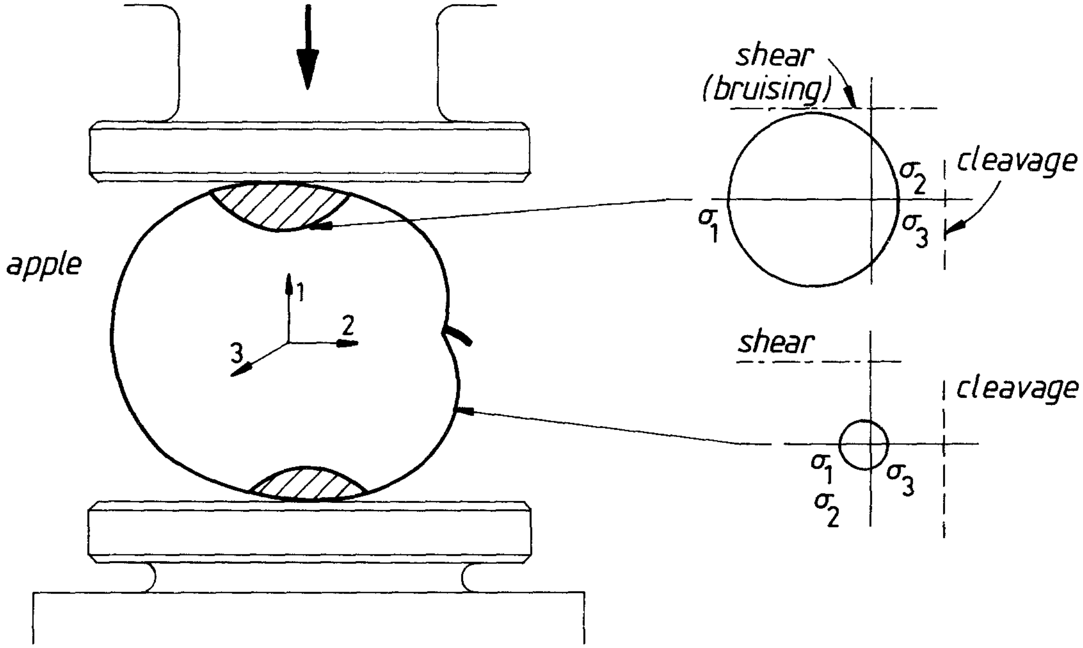

Figure 6 Qualitative representation of failure conditions in apples under compression showing bruising (shear) and cleavage limits superimposed on Mohr's circles.

The energy absorbed in bruising is given by

$$E_{\text{abs}} = E_{\text{in}}(1-\alpha-\beta)$$

where E_{in} is the energy input, α is the recovery ratio and β is the hysteresis ratio. The energy absorbed per unit volume of bruised tissue becomes a measure of the bruise resistance of apple tissue and values derived from Table III are given for all loading rates in Table V. For the impact results a hysteresis ratio of 0.3 is assumed.

The bruise resistance of these apples for slow loading rates is constant at 0.054 Jm^{-3} and is 0.062 Jm^{-3} under impact conditions. Since bruising results from cell bursting, and cells burst when the cell walls fracture, it may be argued that, while bruising on the bulk material level is a shear failure, bruising on a cellular level is a fracture phenomenon. In this case, a fracture toughness figure can be derived from the data in Table III. Assuming a cell diameter of 200 μm [1] the total area of one cell thick tissue equivalent to the bruised material can be calculated from average bruise volume figures. If a crack is assumed to have propagated by bursting every cell then the area of new crack surface formed is twice this calculated value. The energy dissipated per unit area of crack surface can then be derived. The calculated figures are given in Table V. The apparent fracture toughness is 5.4 Jm^{-2} for quasi-static compression and 6.2 Jm^{-2} for impact.

The fracture toughness under tensile loading of tissue from the same batch of apples has been investigated by Schoorl and Holt [18]. In these tests, the energy required to propagate a crack

TABLE V Bruise resistance, in Jm^{-3}, and apparent fracture toughness, in Jm^{-2}, of apples under quasi-static and impact compression

	Loading rate			
	20 mm min^{-1}	50 mm min^{-1}	100 mm min^{-1}	3.1 m sec^{-1}
Bruise resistance (Jm^{-2})	0.055	0.054	0.053	0.062
Apparent fracture toughness (Jm^{-2})	5.5	5.4	5.3	6.2

across a 10 mm x 10 mm specimen was measured. The fracture toughness calculated from these tests was 200 Jm^{-2}. Comparing the values in Table V with this, it is apparent that in bruised tissue only a small proportion of the total number of cells is fractured. On this basis 2.7% of cells burst under slow loading and 3.1% burst under impact. This analysis is supported by the form of the force–deformation curve shown in Fig. 3a, where bruising is seen to occur intermittently during compression. These yield events [1] are the result of layers of cells bursting along constant shear boundaries and this is supported by Fig. 4 which shows definite layering within the bruised region. Between each layer the majority of cells remain unbroken and even along the layers groups of cells survive. There is a strain rate effect and the bruise resistance and apparent fracture toughness are higher under impact conditions than under quasi-static compression, perhaps due to the larger proportion of cells which are damaged.

5. Conclusions

These investigations show that there are three energy dissipative mechanisms operating in both potatoes and apples under slow compression and impact loading. The parameters which describe these mechanisms, namely, the hysteresis ratio, β, the recovery ratio, α, and the fracture toughness, in Jm^{-2}, thus become important properties for investigations of damage in these two crops. The work supports the application of generalized fracture mechanics to certain biological materials to interpret the dissipation of energy input during handling, processing and transport.

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