APPLICATION OF FRACTURE MECHANICS TO THE TEXTURE OF FOOD

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Abstract. The fracture mechanics of food is a rational and useful branch of materials science which can yield information of more general interest. The critical stress intensity factor, K_{IC}, is a valid replacement for the organoleptic (sensory) assessment of "hardness" or "crunchiness" in fruit and vegetables and suggests that crack initiation and propagation in these foods is controlled by factors similar to those found in engineering materials. By contrast "crispness" is a distinct and separate parameter whose origin and control will require an understanding of the fracture behaviour of glassy cellular materials.

1. INTRODUCTION

Food is judged to be acceptable mainly on the basis of two criteria: flavour and texture. The first question is – what textures do we like and why? This has to be given a selective advantage in the evolution of humans and plants, otherwise why would we show a preference and why would plants make bits of themselves so delectable? Theories exist for the evolution of materials "meant to be eaten". For instance fruits gain by having their seeds dispersed and deposited with an ample supply of fertiliser. "Crispness" or "crunchiness" must indicate that the food will be good or safe to eat (or they would not be indicators of good quality food), presumably indicating freshness. Additionally crisp or crunchy food will not only require less energy to chew but can be chewed ("processed") more quickly. Therefore a larger amount of a crisp food can be eaten within a given time and the animal can either eat more or give itself more time for doing other things such as foraging for more food, having sex, etc.

The time-honoured way of measuring the 'texture' (whatever that really is) of food is to ask someone to eat the food and say what they thought of it. Groups of people are trained to report as objectively as possible on the perceived properties of the food items, using everyday terms whose definition they try to agree. These people, now constituting an organoleptic or taste panel, represent the typical consumer and must therefore give the responses which might be expected of such a person. They also try to standardise the way they eat the food items. This type of measurement is subjective.

An objective test which has worked fairly well with crisp and crunchy foods uses the noise made when the food is chewed [1]. However, the noise level is not entirely a function of the food item. The acoustic properties of the chewer, such as the size and shape of the resonating head cavities, can have an important, even over-riding, effect [2]. Nor is it possible to equate the intensity of the noise with the fracture properties of the food, a problem endemic with techniques using acoustic emission. The ideal solution would be to translate "crispness" into a form which can be described by materials science, and measure independent parameters at the material and structural levels which can be related to, and preferably account for, the defined concept of crispness.

Ultimately the aim would be to translate the descriptors used by sensory panels into materials science terms, but there is no satisfactory materials definition for food textures. Instead there is a long line of largely unsuccessful attempts to apply materials science to food texture. Concepts such as scaling effects in fracture mechanics, whereby a smaller piece of material will need a greater density of strain energy before it will break (or may not break in a brittle fashion at all, but plastically), are rarely appreciated by the food texture testers. At the same time the materials community is being quite logical and consistent, but singularly fails to explain itself properly to the food community and anyway cannot easily cope with the morphological complexity of food items. For instance as the piece of material under examination gets smaller, the inhomogeneities become more important, since they will have a greater proportional effect on mechanical performance. This is especially true of dry crisp materials, where high stresses are necessary to break a predominantly glassy starch-based material. The required forces are reduced by reducing the density of the material, either by introducing air which results in a cellular material (puffed foods and "expanded starches") or by starting off with a cellular material such as a piece of plant (a fruit or storage organ). The inhomogeneities range from 100 μm or so (potato cells) to a mm or more (some light snack foods). These sizes are of the same order as the size to which food particles are normally reduced by chewing (of the order of a millimetre) and so are clearly important in textural terms.

Success in understanding the mechanical properties of materials suggests that we should be able to predict the perceived texture of a food from the interaction between its mechanical properties and the processing conditions within the mouth. However, few mechanical tests have ever been shown to be correlated with sensory assessment of the texture of foods [3]. Such assessment involves interactions between the material properties of the food and its structure, complex stress states and interactions with lubricated oral surfaces. It is therefore hardly surprising that attempts to correlate sensory assessments and mechanical tests are often incon-clusive, especially if the problem is approached in a simplistic manner. With better understanding, assess-ment of the textural aspects of foods might be made more quickly, cheaply and sensitively and, since the mechanical parameters can be referred to specific aspects of the shape, chemistry, water content etc of the food item, quality control would become more of an objective science and so rendered much easier.

Recently Lucas (pers. comm.) has taken a more abstract approach using the stiffness (E) and the work of fracture (R) of the food item. Taking the critical stress intensity approach,

$$K_{IC} = C_1 \sigma_F a^{0.5} \tag{1}$$

where σ_F is the fracture stress, C_1 is a constant and a is the depth of indentation made by a tooth biting on the food item. The same result can be expressed using Griffith's approach:

$$\sigma_F = C_2 (ER/a)^{0.5} \tag{2}$$

where E is the Young's modulus and R the toughness of the food item. Under ideal loading conditions, in the absence of boundary conditions, $C_1 = C_2 = \pi^{0.5}$. These conditions cannot apply to a small item of food in the mouth so, in combining these two equations, Lucas defines a new constant:

$$K_{IC} = C_3 (ER)^{0.5} \tag{3}$$

Lucas has then suggested fragmentation criteria based on the way in which different types and shapes of food item are dealt with in the mouth. With "hard" foods, where forces are limiting, the rate of breakdown during chewing is governed by $(ER)^{0.5}$. In passing, he has also shown that if the breakdown of particles is governed by displacement, as with soft foods, then the criterion is $(R/E)^{0.5}$ for thick blocks of food and R for thin sheets. With a variety of fruit and vegetables, his results show that the fragmentation criterion for "hard" foods, calculated from independent measurements of R and E, is met very precisely.

2. HARDNESS AND CRUNCHINESS (BUT NOT CRISPNESS)

We are in the process of hunting down Lucas' criteria using the organoleptic response to the texture, thus bridging the gap between subjective aspects of food science and fracture mechanics. In a series of experiments investigating the texture of fruit and vegetables (Cucumber, carrot, celery, and 3 varieties of apples), ten female organoleptic panellists aged 33-55 years attended each morning for a working week of 5 days. The panellists had been selected for their sensory acuity and their verbal ability in describing food flavours and textures via sensory screening tests. They had received training in sensory profiling techniques and all had participated in previous sensory profiling projects involving the assessment of fruit, vegetables and other food products. In a discussion group they tasted all 6 products and generated 15 descriptors. Eight descriptors were defined for assess-ment on first bite with the front teeth (incisors). The remaining 7 attributes were assessed during chewing with the back teeth (molars). The list of attributes together with their definitions is shown in Table 1. The fracture mechanics was relatively simple, determining K_{IC} using a notched beam in 3-point bending.

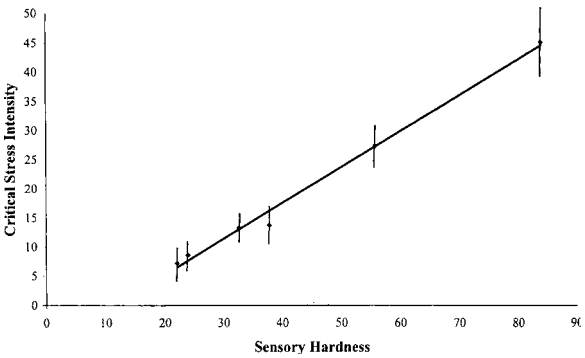


Fig. 1. Correlation between sensory and fracture data for "hardness"

When the results were tabulated and graphed, R^2 for critical stress intensity vs sensory "hardness" was 0.992, (Fig. 1) and vs sensory "crunchiness" it was 0.996. Therefore from a statistical point of view hardness and crunchiness are identical, both at first bite and when the molars are used. More important, the critical stress intensity, K_{IC}, tracks the organoleptic results for hardness (and crunchiness) quite remarkably well. "Crispness" bears a much less good relationship to the critical stress intensity factor (Fig. 2) with R^2 = 0.448, so the hypothesis that crispness and stress intensity factor might be related can be rejected. The relationship of K_{IC} with other of the sensory parameters was explored, but was nowhere near as significant as with hardness and crunchiness. Also the relationship *between* the sensory parameters was explored showing that both pitch and loudness of noise are strongly correlated with sensory hardness. Duration of noise was not correlated with anything. Thus the noise parameters were redundant, although loudness and

pitch were well correlated (R^2 = 0.9442). Crispness correlated with none of the other parameters.

It is clear that both "hardness" and "crunchiness" of fruit and vegetables ("wet crisp materials") are closely related to the stress required to start a crack running through the sample. However, K_{IC}, is a quasi-static parameter which perhaps is why it does not correlate with crispness. There is also the implication that the main fracture events in foods which register as "hard" or "crunchy" must take place in the relatively small process zone at the tip of a notch.

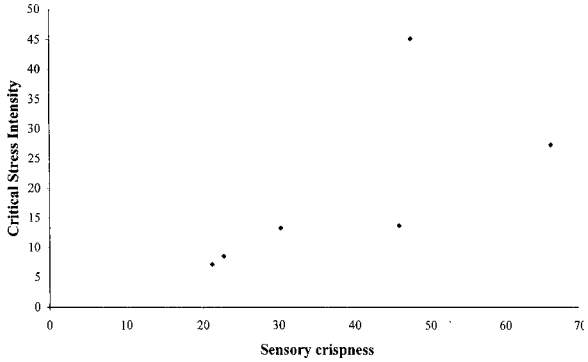


Fig. 2. Lack of correlation between mechanical and sensory data for "crispness"

3. CRISPNESS

Crispness can be defined as the textural or sensual experience of eating a food item which fails in a brittle manner (i.e. very suddenly and with relatively little deformation) at a lowish load. This is in distinction to jelly, which has a low work to fracture (i.e. is brittle) but is so soft that it deforms a relatively long way before fracture, and in distinction to many fruits and vegetables, especially raw, which are brittle but fail only at relatively high loads, being described as "hard" or "crunchy" [4]. "Crisp" materials are generically described as brittle stiff cellular materials [5] derived either from expanded starch or from starch-containing cellular materials such as potato. They are made brittle by deep frying which removes moisture and makes them both glassy and waterproof so that they do not absorb further water [6].

Militating against the ease of fracture of the crisp is the presence of empty spaces (cells or air pockets) within the crisp food which can act as crack stoppers by effectively enlarging the radius of curvature of the crack tip and increasing the compliance of the process zone. Heterogeneity is therefore an important adjunct to brittleness in generating a crisp texture. The few natural cellular materials which have so far been investigated have a fairly idealised (uniform) distribution of cell size and shape [5]. But heterogeneity of cell size can significantly affect the distribution and dissipation of strain energy at fracture [9,10]. The size of these holes, how to control hole sizes in relation to thickness of the crisp and what the distribution of hole sizes might be (monodisperse, polydisperse, etc. – probably easier to control in an expanded starch product) are therefore all important to the control of crispness but have not been systematically explored. In some unpublished experiments, Vincent and Khan examined crisps made from Saturna potatoes. Before frying at 180C the slices were all given a cold wash for 1 min, then A: hot wash (2 min); B: 2% NaCl wash (2 min); C: 0.5% CaCl wash (3 min); D: no further treatment. A taste panel ranked them for crispness in the order A D C B (more crisp >> less crisp). The spectrum of size of fracture events [11] showed that "crispness" correlated with more and larger fracture events. Image analysis showed that this in turn was related to the number of air cells and their size (more and smaller cells result in less crisp texture) and the thickness of the walls between the cells (the cells collapse on cooking, so larger cells result from the fusion of smaller ones and the cell walls adhere, increasing the thickness – thicker walls give crisper texture).

Sensory crispness may be related to the rate at which the force applied by the jaw closing muscles drops when the material fractures; this drop in load may also be detected by sensors in the soft tissues around individual teeth. As the force on a food item increases so does the deformation (Fig. 3). The object then starts to break. If the material is stiff and brittle the fracture will travel quickly resulting in sudden unloading of the muscles; this is seen as a sudden drop in load. The fracture is then somehow inhibited and stops, only to start again as the crisp is deformed further. The magnitude of this effect is probably important; for instance a series of a few large events is typical of a "quality" potato crisp; a longer series of smaller events is typical of an average, light potato crisp (Fig. 4). As the events become larger and fewer, there is a transition from "crisp" to "hard" texture; conversely as the events become smaller and more frequent, the texture becomes "crumbly".

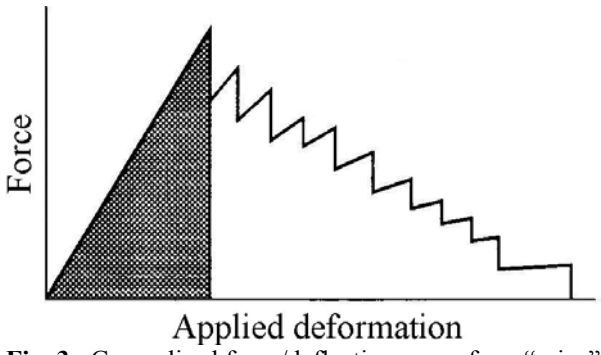


Fig. 3. Generalised force/deflection curve for a "crisp" item of food

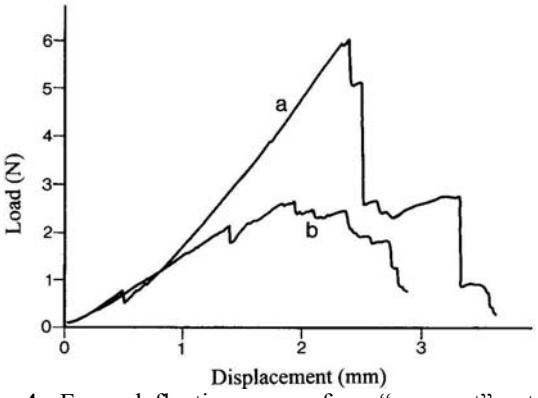


Fig. 4. Force deflection curves for a "gourmet" potato crisp (a) and an "ordinary" potato crisp (b).

Several people have used information from the force/deflection curve obtained from a mechanical fracture test of a crisp item, but they have mostly tried to transform it into a single, apparently simple, number which usually bears no relation to any material properties and is merely a mathematical construct [7]. This has the advantage of succinctness but gives no information about the material or the way it fractures and therefore cannot predict fracture behaviour from a set of precepts. One fairly obvious method of assessing crispness, developed specifically to quantify brittle fracture, is the Weibull statistic [8]. To my knowledge this approach has never been applied. However it is still only descriptive, giving an assessment of how likely something is to break rather than what causes it to break.

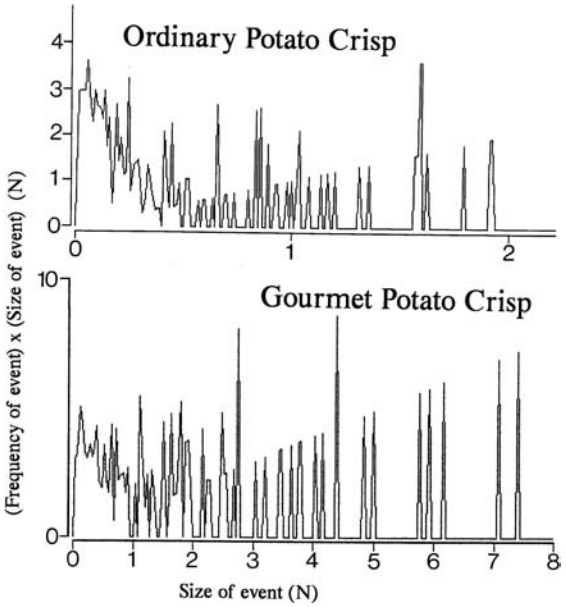


Fig. 5. Force drop spectra for the crisps shown in Fig. 4. Each spectrum is constructed from the pooled data from breaking about 30 crisps.

In simple mechanical tests in which a crisp food item is broken in something approaching 3-point bending, the primary data trace the number of times the force has dropped (fracture 'events'), and the size of the drop. Since the larger events are much rarer, in order to produce an understandable visual record of the test they have been multiplied by their size to make them more obvious (Figs 5 - 7). The area under the graph thus bears some relationship (depending on the work of fracture of the material) to the total work done. The size of the force drop is also related to the area of the fracture surface generated by the release of strain energy associated with the reduction in force. Therefore the smaller events to the left of each graph are presumably due to individual small cells or granules, or groups of small cells or granules, fracturing. These events may be associated with "ease of shattering" or "crumbliness" (words commonly used in sensory panels) and will, individually, require only a very small amount of strain energy. Such small events form a large part of the response of potato crisps (=chips), biscuits and peanuts which have a fine structure. The larger events suggest "crispness"; ones which are larger still (since they require a higher force at the start) probably indicate "hardness" of the crisp, as might be detected in the more expensive varieties. The largest events seem likely to be associated with "crunchiness", suggesting that the horizontal axis of these spectra can be divided up into a series of regions each characteristic of a type of texture, progressing (left to right) from crumbliness through crispness and crunchiness to hardness. If indeed these textures are distributed along a mechanical continuum, it is not surprising that they should be difficult to distinguish by a sensory panel.

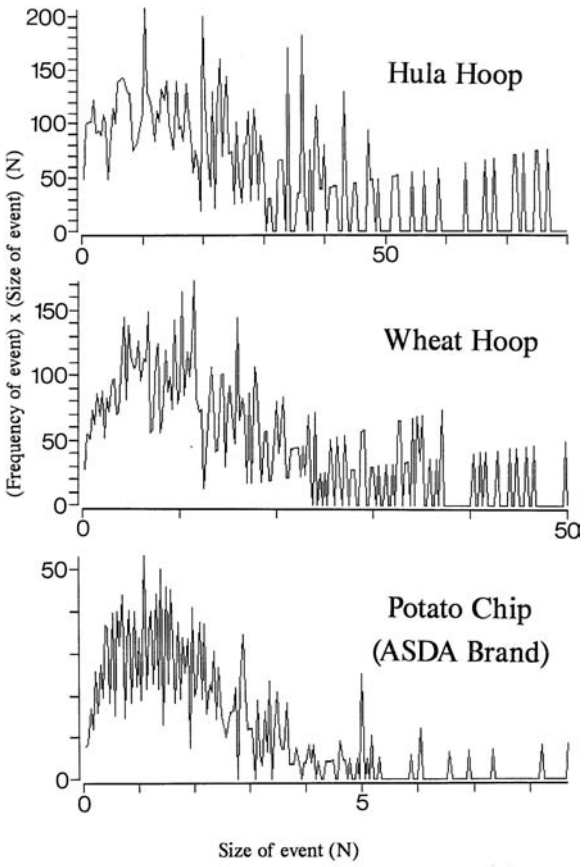


Fig. 6. Force drop spectra for some expanded starch crisp products, all of them cellular materials.

Any crisp will, when chewed, be reduced to particles of approximately consistent size before being swallowed, so it follows that crisps of comparable size will require comparable amounts of fracture energy to chew them. "Crispness" ranking could then be achieved objectively as the ratio between total force drop during fracture and the total length of the fracture path which can easily be estimated by measuring the size distribution of the particles produced and estimating their perimeter. The trick in controlling crispness might then be redefined as controlling the partitioning of a finite amount of strain energy between competing fracture events of different sizes. In a crisp with large amounts of energy used in small fracture events, there will be relatively little energy available for the large events, since it will never be able to build up to a level sufficient to drive a large crack through the material.

It is also likely that there is a relationship between crispness and the velocity with which the crack is propagated, which in turn will affect the response of the physiological mechanisms. In order for the crack to propagate slowly the material would probably have to be rather damp and the sensation of crispness would be lost. Certainly there is a relationship between crack velocity and the magnitude of an acoustic signal [12] which suggests that the mechanical tests should be filmed at high speed. The velocity of propagation of the crack can then be measured, and the places where it starts and stops determined. It will then be possible to equate a crack with the force-drop it engenders at various points during its development. The speed of propagation of a crack is not uniform; in some early experiments using a relatively low sampling rate (20 Hz) the unloading process could be seen to be slow at the start and end of the fracture and faster in the middle as judged by the spacing of the points on the load axis. But since the fracture was not filmed these variations could not be equated with any other events.

The energy required for fracture to propagate has to be stored in the material or its surroundings and delivered to the crack tip in the form of strain energy. In the mouth this energy can be stored as a change of shape of the crisp and in the jaw muscles. In a stiff mechanical test machine, the energy needed for fracture is entirely stored in the crisp. This partitioning of strain energy may itself be important, since it is unlikely that muscles, being viscoelastic, can deliver their strain energy as quickly as a stiff testing machine.

In addition to quantifying crispness objectively, we need to know the limits of what is detectable (at the lower end of the crispness stimulus) and what is acceptable (at the upper end). This, too, can be approached objectively if the physiological means of measuring crispness are accounted for. For instance the teeth are hung in a web of collagen fibres with sensors that can detect forces as low as 0.05 N or so. Similarly the cheek muscles tend to stop contracting if the food item breaks suddenly, and the smallest sudden drop in load they can detect is of the order of 0.05 N [13]. This lower level of force therefore sets a lower limit on the size of brittle fracture event which would be expected to give the stimulus "crisp", at least in physiological terms. Its exploration requires a subject to chew a characterised crisp food item whilst the cheek muscle is being monitored using electro-myography (e.m.g.) and to relate the sensory experience both to the e.m.g. trace and to the fraction of the fracture events which occurs above and below the detectable force limit. The upper acceptable limit is probably set more by the presence in the mouth of sharp shards of glassy starch than the force needed to break the food item; such shards can puncture the epithelial lining of the mouth and cause bleeding (personal experience!).

4. DISCUSSION

In the study on hardness and stress intensity factor, the sensory tests took 25 working days to perform. "Hardness" and "crunchiness" represented about 25% of the total sensory data set, making a total of about 6 working days. This data set required extensive work both entering the data into the statistical package and in the analysis. In contrast the mechanical tests required 75 measurements which, at about 5 minutes per test, took about 6.25 h. Statistical analysis was straightforward taking about 30 minutes. So for data of arguably better quality and usefulness (since materials science can give much extra information about the origin of the factors leading to the magnitude of the critical stress intensity), rather less than a fifth of the time (and therefore expenditure) was required. In addition less laboratory space and facilities were needed, adequately discounting the expenditure for a mechanical testing device, which can be used for all sorts of other tests anyway. Clearly there is much advantage to using a well-characterised mechanical test for measuring the texture of food.

The temptation is to see how many other food items, for which "crunchiness" or "hardness" are sensory parameters, can be equally well characterised by the critical stress intensity factor. I see no reason why this should not work, and suggest that a suitable food item would be biscuits. Since these can be formulated, it would be possible to quantify the effects of the various parameters of manufacture independently of each other in a series of controlled experiments and to calculate in absolute terms the outcome of altering or correcting the processing variables and the ingredients in terms of hardness and crunchiness. This is an improvement on Quality Control tests in that the results are applicable over a wide range of products whose sensory profile is affected as much by morphology of the product as by the properties of the materials from which it is made. Such predictive power is a result of using concepts from materials science. There are doubtless other applications of this fracture mechanics approach which will occur to the astute Sales Manager.

It is probably still wise to defer dismissal of organoleptic tests, at least for the initial comparison of texture of food with K_{IC}. Food is more complex in structure than most of the materials of engineering whose fracture behaviour has been quantified and so the materials tests need at least to be validated in each case.

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First Bite, Incisors

Attribute	Definition
Hardness	Amount of force required to break sample
Crispness	Fractures in an abrupt manner after applying a relatively small force on the sample
Crunchiness	Fractures after applying a higher force on the sample than for Crispness
Noise-pitch	Overall frequency of sound emitted from the breaking sample. Scored from LOW to HIGH.
Noise-duration	Length of time for which noise was emitted from the breaking sample
Noise-loudness	Volume of sound emitted from the breaking sample
Breakage	Speed of fracture – scored from SLOW to FAST
Clean break	Way in which the sample breaks, whether the crack propagates suddenly and completely or in a cascade of smaller fractures

Second Bite, Molars

Attribute	Definition
Hardness	Amount of force required to break sample on first chew with molars
Crispness	Fracture in an abrupt, brittle manner after applying a relatively small force on the sample on the first chew with the molars
Crunchiness	Fractures after applying a higher force than for crispness on the first chew with the molars
Noise-pitch	Overall frequency of sound emitted from the sample on the first chew with the molars. Scored from LOW to HIGH.
Noise-duration	Length of time for which noise was emitted from the breaking sample
Noise-loudness	Volume of sound emitted from the breaking sample
Speed of breakdown	Speed at which the sample breaks down into a state ready for swallowing. Scored from SLOW to FAST.

Table 1. Definitions of the attributes used by the sensory panel.