

FEEDING AND THE TEXTURE OF FOOD

Edited by

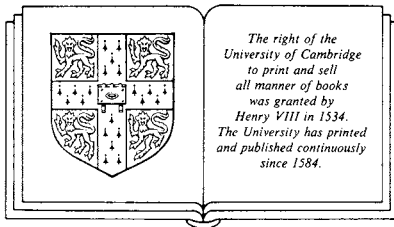
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G. JERONIMIDIS

Mechanical and fracture properties of cellular and fibrous materials

Most foods, natural or manufactured, have structures which are either cellular or fibrous or both. Meat, fish and poultry owe their distinctive texture to the fibrous nature of the muscles and to the way in which they fracture with fibre separation. The crispness of fresh fruit and vegetables is a consequence of having moderately large cells filled with liquid, pressurised by osmotic turgor and adhering to each other. On being bitten or chewed the cells can either rupture, releasing their contents as in a crisp apple, or separate from each other as in a mealy apple. When significant amounts of fibres or fibre bundles are also present, as in asparagus or spinach for example, the texture of the cooked vegetable is affected considerably and the material is perceived as tough because of the difficulty in breaking the fibres. Extrusion-cooked products are often designed to be heterogeneous so as to introduce desirable textural attributes; this can be achieved, for example, by producing cellular structures where cell size and cell wall thickness can be varied.

The perception of food texture depends on specific properties of the food materials themselves (resistance to deformation and fracture, appearance, taste, etc.) and on the interactions between the mouth and the foods through teeth, muscles, taste buds, etc. (Williams & Atkin, 1983). Biting and mastication in particular play a central role in determining the acceptability of foods and this chapter concentrates on the mechanical properties of food materials relevant to these aspects. The elastic, strength and fracture properties of heterogeneous substances will be reviewed and discussed in relation to those textural attributes which depend on them.

Mouth–food interactions

When food is placed in the mouth and biting or chewing takes place, the teeth apply a *deformation* to the food material through the action of the muscles. The distinction between the application of a deformation and

that of a load is important because in many instances the stability of cracks depends on which variable is controlled (Atkins & Mai, 1985) and this, in turn, has an effect on the choice of test methods which need to be used for proper characterisation of fracture properties.

As a result of the applied deformation, the food material responds elastically or viscoelastically at first, depending on the rate of application of the deformation, until some critical strain value is reached when either flow or fracture or a combination of both will take place. The *stresses* induced in the food materials will depend on the geometry and size of piece put in the mouth, on its elastic or viscoelastic properties and, in the case of anisotropic materials such as meat, also on the orientation of the piece with respect to the teeth.

The stresses associated with biting and chewing are seldom simple states of stress such as uniaxial tension or compression; heterogeneous food materials are particularly sensitive to complex stress states. The existence of multiple failure mechanisms at different levels of structure leads to several failure modes, each associated with a particular stress or combination of stresses, increasing the complexity of characterisation and analysis. For an isotropic substance which fails by plastic flow, for example, the yield strength is the only strength parameter needed because tensile, compressive or shear strength can all be associated with a single yield strength value. Even the simplest fibrous composite, on the other hand, requires five strength parameters for full characterisation (Jones, 1975).

When food materials are processed in the mouth the types of failure which are associated with comminution can be subdivided into four broad categories:

- brittle (boiled sweets, chocolate, hard biscuits, nuts, etc.),
- ductile (soft cheeses, soft toffees, etc.),
- ductile-brittle (chocolate, hard cheeses, etc.),
- fibrous (meat, fish, etc.).

Cellular materials, liquid-filled or not, can be assigned to either of the first three categories depending on cell size, properties of cell wall materials and adhesive strength between cells. In many manufactured foods such as air-filled chocolate products and starch-based extrusion-cooked materials, pseudo-ductile behaviour at the macroscopic or mouth level can be incorporated in the design, although the failure is essentially brittle at the microscopic level. In apples, for example, the specific design of the cellular structure can produce brittle or tough fractures during the

first bite, depending on the type of apple and on orientation in the mouth (Khan, 1989). This is an illustration of how important it is to relate the level of heterogeneity of a given food material to the absolute size and shape of the volume introduced into the mouth for comminution. A proper understanding of mouth–food interactions in relation to texture must consider these aspects especially for predictive and design purposes.

All materials are heterogeneous at some level of structure or another and the mechanical properties that are measured are the result of some averaging process over a given volume. Foods vary considerably in their heterogeneity, both in size and in kind, and this does affect those textural attributes which depend on measured mechanical properties. The definition of a *representative volume* and of the rules to apply to it for averaging purposes is essential. The various failure modes defined earlier are not absolute but depend on these scale effects. A brittle material may deform in a ductile manner if sufficiently small and, conversely, a ductile material can fail in a brittle manner if sufficiently large. The difficulty lies in defining what ‘sufficiently’ means but there are experimental and theoretical techniques available for the purpose (Hashin, 1962; Mai & Atkins, 1980).

When dealing with food materials the effects of water need also to be taken into account. Water can act as a plasticiser (Lillford, 1988), altering properties of the base materials, or play a more direct structural role as in liquid-filled cellular foods such as fresh foods and vegetables (Jeronimidis, 1988; Gibson & Ashby, 1988). In both instances the presence of water can alter the type of failures produced by mouth action, changing a food material from brittle to ductile or pseudo-ductile, with associated differences in perceived texture. In this respect it is particularly important to consider the water pick-up of the food *after* introduction into the mouth, the rate of pick-up and its short-term effects on elastic and fracture properties.

Heterogeneous materials: structure and properties overview

In dealing with heterogeneity and mechanical properties of food materials it is convenient to use definitions and descriptions already established for other classes of materials (Cottrell, 1964). This is because most of the theoretical and experimental techniques have been developed in that context and have led to unambiguous definitions of properties which are useful in avoiding confusion. Terms such as stiffness, strength, fracture, ductility, etc. have very precise meaning in engineering and materials science, whereas, all too often, the corresponding terminology

associated with food textural studies is less precise: crispness, crunchiness, firmness, etc. Indeed, part of the development of food mechanics as a discipline will require the establishment of appropriate methodologies to relate the engineering terms to those of the food textural studies.

From the point of view of their physical state all materials, including foods, can be subdivided into solids, liquids and gases. The distinction between the last two is straightforward but the same is not true for the first two, especially in relation to mechanical properties, viscoelastic behaviour and water effects. Depending on the rate of deformation, the temperature and the amount of water pick-up, the same material can be looked upon as a solid or as a more or less viscous liquid. The same piece of chocolate will fracture into several smaller bits when cold and deformed quickly, exhibiting all the characteristics of a brittle solid, but will flow irreversibly as a liquid if the temperature is sufficiently high or the rate of deformation sufficiently low. As mentioned earlier, however, even a cold piece of chocolate loaded rapidly can yield and flow if it is very small.

Within the materials which under the given circumstances behave like solids, a further distinction needs to be made between isotropy and anisotropy. This affects the elastic as well as the strength and fracture properties and will be discussed later in greater detail. Anisotropic food materials owe their anisotropy to their multiphase composition. Characteristic aspect ratios and linear dimensions of particles, voids and fibres with respect to representative volume determine not only whether or not the material should be considered homogeneous but also whether or not it should be considered anisotropic. If, for example, a manufactured food contains fibres which are too small to be perceived by the teeth and locally aligned, the material is strictly speaking microscopically heterogeneous and anisotropic; but if the volume under consideration is much greater than the representative volume it will behave macroscopically as a homogeneous isotropic material. Conversely if such a material needs to be redesigned to introduce specific textural attributes associated with heterogeneity and anisotropy, the phase dimensions will need to be changed or higher levels of structure will need to be introduced during processing.

Isotropic and anisotropic food materials can further be subdivided according to the type and level of deformation required to initiate flow or fracture. Some foods, which are best described as rubbery, will deform reversibly up to comparatively large strains (10% or more). Given the limited level of deformation that mouth and teeth can apply it may not be possible to reach the strain levels at which fracture will occur and they may well be perceived as tough, although they may not be tough at all in

an engineering sense. In this case comminution in the mouth requires a specific cutting action from the teeth. The whole process is like trying to bite into or chew a rubber elastic band; rubber is a fairly brittle material. This distinction between low strain and high strain fracture is also relevant to the behaviour of gas-filled cellular structures as demonstrated, for example, by the differences in compressibility and compressive strength between fresh and stale bread.

The techniques which need to be used to study the mechanical properties of food material are no different conceptually from those already established with other types of materials, but difficulties do arise both experimentally and theoretically. Many foods cannot be obtained in large enough sizes or regular enough geometries to satisfy the validity requirements that certain types of mechanical test demand. As an example of this, consider a simple three-point bending experiment to determine Young's modulus or bending strength (Fig. 1). If the material is isotropic and homogeneous, even a small sample will give accurate results so long as the span is about ten times the thickness. If on the other hand the material is moderately anisotropic and heterogeneous, the span to thickness ratio will have to be 100 or more before sensible results are obtained (Fellers & Carlsson, 1979). Similar considerations apply to fracture testing as mentioned earlier.

Theoretical difficulties arise from the complexity of anisotropic and heterogeneous food materials, especially in relation to the predictions of *effective properties* as the average of complex interactions at specific levels of structure within appropriate representative volumes. Micro- and macromechanics techniques used successfully with artificial fibrous composites and cellular solids are available but the limits of applicability need

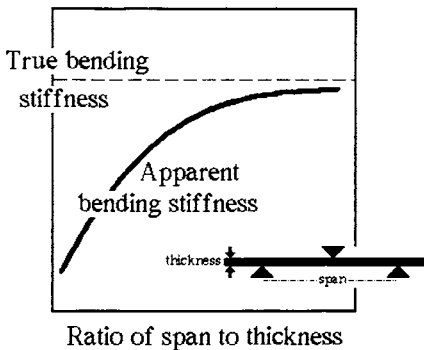


Fig. 1. The effect of changing the span-to-thickness ratio on the measurement of stiffness in bending in an anisotropic material.

to be established and assessed for each particular case (Ashby, 1983; Hull, 1981). A particular problem exists with high strain anisotropic materials, about which little is known even for much simpler materials than natural or artificial foods (Jeronimidis & Vincent, 1984).

Fibrous materials

Elastic properties

The elastic properties of fibrous composites are derived from micromechanics principles which take into account the interactions between the various phases. The simplest conceptual model consists of parallel, infinitely long fibres embedded in a 'matrix' of lower stiffness and lower strength than the fibres (Fig. 2). Knowing the elastic properties of fibres and matrix, the properties of the composite are obtained from first principles (Jones, 1975).

If the material is loaded in tension or compression parallel to the fibre direction and if the elastic strains in both phases are assumed to be equal, the composite Young's modulus E , in the fibre direction is given by the 'rule of mixtures':

$$E_{\ell} = E_f V_f + (1 - V_f) E_m \quad (1)$$

where the subscripts f and m relate to fibres and matrix, respectively, and ℓ stands for longitudinal, i.e. parallel to fibres. V_f is the volume fraction of fibres in the system.

When the tensile or compressive load is applied normal to the fibre direction (t for transverse) the fibres and the matrix are assumed to carry the same stress and the transverse Young's modulus is given by:

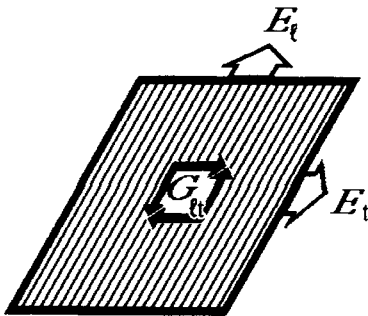


Fig. 2. Unidirectional thin composite lamina – principal directions of anisotropy. E , Young's modulus; G , shear modulus; subscripts ℓ , t , longitudinal, transverse.

$$E_t = \frac{E_f E_m}{E_f V_m + E_m V_f} \quad (2)$$

A similar expression is obtained for the 'in plane' shear modulus, G_{et} , of the material:

$$G_{et} = \frac{G_f G_m}{G_f V_m + G_m V_f} \quad (3)$$

By the same type of argument the principal Poisson's ratio can also be derived from the corresponding values for fibres and matrix:

$$\nu_{et} = \nu_f V_f + \nu_m V_m \quad (4)$$

This Poisson's ratio corresponds to the *induced strain* ε_t in the t direction for an *applied strain* ε_ℓ in the longitudinal direction and is defined as:

$$\nu_{et} = -\frac{\varepsilon_t}{\varepsilon_\ell} \quad (5)$$

There is also a 'minor' Poisson's ratio, $\nu_{t\ell}$, which measures the induced longitudinal strain for a given applied transverse strain.

Four out of these five elastic constants are independent and need to be measured accordingly. The minor Poisson's ratio is related to E_ℓ , E_t and ν_{et} by:

$$\frac{\nu_{et}}{E_\ell} = \frac{\nu_{t\ell}}{E_t} \quad (6)$$

Even the simplest fibrous composite requires twice as many independent elastic properties as an isotropic material where E and ν or E and G or G and ν are sufficient for full characterisation.

This analysis applies to thin composite layers where the thickness can be considered small compared to the lateral dimensions of the material. When this is not the case a full set of either five or nine independent elastic properties is needed, depending on whether the material possesses a plane of isotropy or not. In theory these properties can be calculated from expressions as those given here but their predictive power is often very limited. The only expressions which have been found to work reasonably well are those for the Young's modulus in the fibre direction and for the principal Poisson's ratio; in the other cases one needs to resort to experiment (Tsai, 1987).

When the fibres have a finite length and are not parallel to each other the expressions given earlier need to be modified to take these factors into account. Equation (1), for example, can be re-written as:

$$E_\ell = \alpha\beta E_f V_f + (1-V_f) E_m \quad (7)$$

where α is a parameter dependent on fibre length and β a parameter dependent on fibre orientation. Expressions for these parameters have been calculated (Cox, 1952):

$$\alpha = 1 - [\tanh(\frac{1}{2} k\ell) / \frac{1}{2} k\ell] \quad (8)$$

where ℓ is the fibre length and k a parameter depending on volume fraction of fibres, shear modulus of matrix and Young's modulus of fibres. As ℓ increases α approaches the value of 1.

$$\beta = \int_0^\pi \cos^4 \theta f(\theta) d\theta \quad (9)$$

where $f(\theta)$ is a function describing the statistical orientation of fibres. When the fibre orientation is random in the plane, $\beta = 1/3$. When it is random in three-dimensional space, $\beta = 1/6$ and when the fibres are all parallel, $\beta = 1$. For orientations which are intermediate between parallel and random, the distribution function of fibre orientations must be obtained first by using microscopy techniques.

It is worth pointing out at this stage that, although the equations for the Young's moduli are equally applicable in tension and in compression, in principle up to the failure strain of the composite, in practice this is seldom the case in compression. Fibre buckling can occur at the very early stages of deformation, especially in low volume fraction composites with relatively pliant matrices (Dow & Rosen, 1965).

Strength and fracture

Strength and fracture properties of fibrous composites can be approached in several ways which should be considered complementary rather than mutually exclusive. The complexity of the materials and the number of mechanisms which can initiate failure and fracture are such that no single body of theory can describe and predict accurately the initiation, evolution and final stages of the irreversible deformations associated with strength and fracture.

A brief outline of the various approaches is given in this section; it is necessarily brief and reference should be made to the relevant literature for a more comprehensive discussion. A distinction is also made between strength and fracture theories; they are obviously related but the methodologies needed for their description are sufficiently different to be dealt with separately.

The simplest theories of strength for fibrous composites are based on the rule of mixtures discussed in the previous section (Kelly, 1973). Assuming that fibres and matrix have the same failure strain, equation (1)

can be extended to give the tensile strength of the composite in the fibre direction:

$$\sigma_{\ell}^* = \sigma_f^* V_f + \sigma_m^* (1 - V_f) \quad (10)$$

where σ^* is the tensile strength of composite (ℓ), fibres (f) and matrix (m). If the fibres and the matrix do not have the same failure strain, which is often the case, equation (10) needs to be modified (Hull, 1981) but its basic structure does not change and it will still show that the composite tensile strength is a linear function of the fibre tensile strength. Equation (10) needs also to be modified if the fibres are not infinitely long or if they cannot be assumed to be so. In this case equation (10) becomes:

$$\sigma_{\ell}^* = \sigma_f^* \left(1 - \frac{l}{2l_c}\right) V_f + \sigma_m^* (1 - V_f) \quad (11)$$

where l_c is the 'critical fibre length' and l is the actual fibre length. The critical fibre length takes into account the fact that in a short fibre composite the stress in the fibres builds up from zero at the two ends to the fibre strength value through shear stresses acting at the fibre-matrix interface as shown in Fig. 3 (Cox, 1952).

Equations (1) and (10) and their modifications have no equivalent when the composite is stressed in compression parallel to the fibre direction, or in in-plane shear or in the transverse direction (tension and compression). This is not altogether surprising because the micromechanisms associated with failure initiation are different in all these cases. Compression failure parallel to the fibre direction is triggered by fibre buckling which depends on the elastic rather than strength properties of fibres and matrix. Transverse strength in tension and compression is

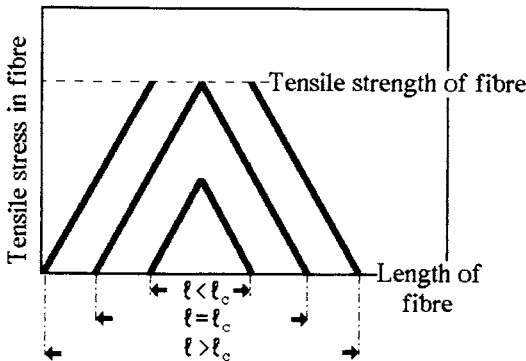


Fig. 3. Fibre stress as a function of fibre length (l) in a short-fibre composite; definition of critical transfer length, l_c .

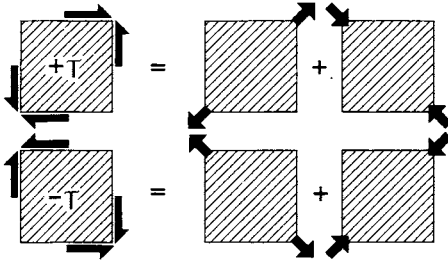


Fig. 4. Positive (+T) and negative (-T) shear stresses in a fibrous material expressed as a combination of tension and compression.

dominated by matrix properties. The shear strength can be thought of as strength under a combined state of stress, one tensile and one compressive of the same magnitude (Fig. 4); one important consequence of this is that the shear strength of anisotropic materials depends on the sign of the shear stress which is not the case for isotropic solids (Ashton, Halpin & Petit, 1969).

Of the five independent strength parameters needed to characterise even a simple unidirectional composite with parallel fibres, only one can be predicted with some confidence from the strength properties of the constituent phases. The others must be determined experimentally. It is also important to note that four out of five strength parameters are matrix-controlled, the only fibre-controlled one being the tensile strength parallel to the fibre direction. This has important implications when complex states of stress are present in these materials, as in the case of fibrous foods during biting and mastication, because the materials can fail almost simultaneously in more than one way making it difficult to identify the precise mode of fracture.

A second approach to the strength of fibrous composites is based on failure criteria. One accepts that the five strength parameters cannot be predicted but so long as they can be measured they can be incorporated into a macromechanical criterion for strength which does not concern itself with the microevents associated with initiation and evolution of damage but only with the final outcome. One important advantage of failure criteria is that they can take into account the interaction between failure modes, particularly important when complex stress states are present. All strength criteria can be expressed in compact form by the following equation (Tsai & Hahn, 1980):

$$F_i \sigma_i + F_{ij} \sigma_i \sigma_j = 1 \quad (i, j = 1, 2, 3) \quad (12)$$

where F_i and F_{ij} are strength related parameters and σ_{ij} are the applied

stresses, three in the simple case of thin composites, two normal stresses and one in-plane shear (a repeated index implies summation over that index).

This kind of failure criterion has been successfully applied to the strength predictions of artificial fibrous composites. Its extension to more complex materials such as fibrous foods should be possible so long as the strength parameters have been measured and the effective state of stress has been determined.

The most severe limitation of failure criteria is that they cannot deal with cracks and crack propagation. This becomes the province of fracture mechanics. In its simple form it deals with the stability of cracks in stressed bodies by taking into account the stress concentration which arises near a crack tip:

$$\sigma = \frac{K}{\sqrt{(2\pi a)}} \quad (13)$$

where σ is the remote applied stress, a the crack length and K a parameter which measures the stress intensity at the crack tip. As σ increases for a given crack length a , K reaches a critical value K_c when the crack propagates in an unstable manner. This works well with brittle or semi-brittle materials where the crack length can be defined fairly precisely. Equation (13) has also been modified in a number of ways to allow for plastic flow at the crack tip. Its application to heterogeneous fibrous composites is debatable because in these materials there is a multitude of microevents associated with fracture which make it difficult to define with any accuracy an initial crack length. Also, crack propagation can develop simultaneously in more than one direction and self-similar crack growth is an implied assumption in equation (13) (Kanninen & Popelar, 1985, pp. 392–436).

A more promising approach to the fracture properties of heterogeneous, anisotropic materials is based on what is known as the 'energy method' (Gurney & Ngan, 1971). This approach is closer to the traditional Griffiths criterion for crack propagation (Griffiths, 1920) and both have the virtue of including an energy dissipation term which can be related to microevents associated with crack initiation and crack propagation (Atkins & Mai, 1985). In its simplest form, the energy method can be written as:

$$Xdu = dE + RdA \quad (14)$$

where X is an applied force, du a corresponding displacement of the cracked body, dE the elastic energy stored in the body, dA the increment of cracked area and R the work dissipated irreversibly to increase the

crack area by dA . With this method the fracture energies related to individual micromechanical events during damage evolution are all incorporated into R . In some instances they can be evaluated independently, either experimentally or theoretically, and their relative importance quantified. In fibrous composites the events associated with microdamage typically include fibre fracture (brittle or ductile), matrix cracking, matrix yielding, fibre-matrix debonding, fibre pull-out, etc.

At this stage of the development of food mechanics it is not possible to suggest a particular method as opposed to another for the study of strength and fracture of food materials. The energy method has been used with some measure of success in meat (Dobraszyk *et al.*, 1987), cheese (Luyten, 1988) and apples (Vincent *et al.*, 1991). The results suggest that properly measured fracture properties can be related to textural attributes. Some work has also been done in relating fracture properties of plant materials to their characteristics as foods (Vincent, 1990).

Cellular materials

Cellular materials constitute a very important class of foods. Those of natural origin include all soft fruits and vegetables; among the manufactured types bread and associated products are widespread across the whole world. More and more cellular 'snack-type' products are being manufactured from a variety of raw materials. In spite of their importance, it is only in recent years that a rational approach to the mechanics of cellular structures has emerged.

Special textural attributes are associated with the progressive collapse of cell walls in air-filled food materials and with the release of cell contents from the liquid-filled structures of fruit and vegetables. In order to preserve, enhance or 'design-in' these desirable features it is important to understand the mechanics of deformation and fracture of these materials. Most of the work done in recent years has followed some earlier studies of polymeric foams, extending the range of applicability of the results and establishing a firm theoretical foundation for analysis (Hilyard, 1982; Gibson *et al.*, 1982; Gibson & Ashby, 1988).

Elastic properties

A crucial property in the study of cellular materials is the ratio of densities between the cellular and the solid phase of the same substance. This provides not only a measure of the heterogeneity of the cellular material but also the link between the modes of deformation and fracture at the

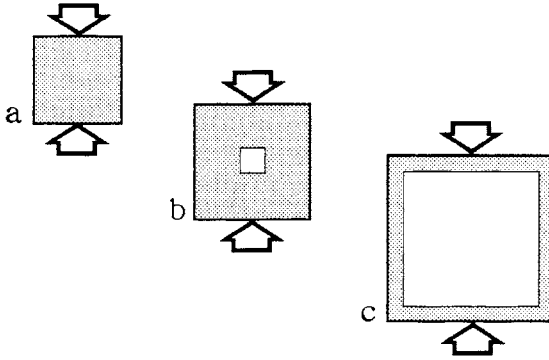


Fig. 5. The transition from a solid to a cellular material (see the text for explanation).

level of a single cell and the macroscopic bulk behaviour of the cellular structure.

Consider for example the three structures shown in Fig. 5 where the total volume of solid material is the same. If a compressive load is applied to material a, the deformation in the solid will be uniform. In material b the bulk of the solid will still experience a uniform state of strain, except for a small volume around the circular hole. Essentially b is a slightly perturbed equivalent of a. In 'material' c, however, the distribution of the solid material is such as to introduce local modes of deformation different from either a or b and its response to the applied load will be significantly different from the first two.

Material b is a high density structure, whereas material c is a low density one. The dividing line between high and low density is somewhat arbitrary but cellular systems with volume fractions of solids of 80% or more are considered to be high density, those with solids fractions of less than 10% are low density. Those in between can be considered to be either high or low density depending on available deformation modes.

The elastic properties of high density cellular solids can be obtained from rules of mixture, assuming that the gas inclusion has negligible properties compared to the solid. For the Young's modulus the following expression is obtained (Jeronimidis, 1988):

$$E_c = E_s \left(\frac{\rho_c}{\rho_s} \right) \quad (15)$$

where E_s is the Young's modulus of the solid, ρ_s its density and ρ_c the density of the cellular structure.

If bending deformations are also included, as will happen in a low density material, the expression for the modulus becomes (Ashby, 1983):

$$E_c = kE_s \left(\frac{\rho_c}{\rho_s} \right) \quad (16)$$

where K is a constant. The major difference between equations (15) and (16) is the different dependence on relative density.

If the cellular structure contains an incompressible liquid which cannot flow from cell to cell (closed cell structure), the interactions between cell walls and liquid must also be considered because the state of stress of the cell walls, and hence their possible modes of deformation are modified by the presence of the liquid under pressure. In effect the liquid under pressure stresses the cell walls in tension, preventing or delaying certain modes of deformation. This is the situation which exists in fruits and vegetables with turgor. The same considerations apply to interconnecting liquid-filled cellular structures where the rate of liquid flow from cell to cell is small owing to viscous and channel size effects (Warner & Edwards, 1988).

The various models presented in this section have been verified for a number of natural and artificial cellular materials. Their application to food structures has also been verified in a simple case not involving liquid-filled systems (Attenburrow *et al.*, 1989).

Strength and fracture

In relation to textural attributes of cellular foods, their compressive strength and fracture properties are perhaps more important than their elastic behaviour. In this case too the relative density of the cellular material provides a link between strength and fracture properties of base substances and cellular structures. Depending on the properties of the solids from which the cellular materials are derived, three modes of failure of the cell struts (open cells) or cell walls (closed cells) are possible: elastic buckling, plastic collapse and brittle collapse. Elastic buckling occurs when the cell struts or walls in compression can undergo significant bending deformations before reaching their elastic strain limit. This depends both on the geometry of the cross-section of the wall or strut and on the mechanical properties of the solid. Plastic collapse follows elastic collapse for ductile materials, which can yield and deform plastically beyond their elastic limit. Brittle collapse is associated with solids with small strains to failure so that brittle fracture occurs before buckling. The expressions for the compressive strength of cellular materials for the three cases are (Gibson & Ashby, 1988):

$$\sigma^* = k_1 E_s \left(\frac{\rho_c}{\rho_s} \right)^2 \text{ (elastic collapse, open cells)} \quad (17)$$

$$\sigma^* = k_2 E_s \left(\frac{\rho_c}{\rho_s} \right)^3 \text{ (elastic collapse, closed cells)} \quad (18)$$

$$\sigma^* = k_3 \sigma_{sp} \left(\frac{\rho_c}{\rho_s} \right)^{3/2} \text{ (plastic collapse)} \quad (19)$$

$$\sigma^* = k_4 \sigma_{sb} \left(\frac{\rho_c}{\rho_s} \right)^{3/2} \text{ (brittle collapse)} \quad (20)$$

In these equations, σ^* is the compressive strength of the cellular structure, ρ_c its density, E_s the Young's modulus of the solid, ρ_s its density, σ_{sp} the yield strength of the solid and σ_{sb} its brittle strength; k_1, \dots, k_4 are constants.

The above expressions can be used to determine the maximum stress that a cellular structure can carry before collapsing reversibly, progressively or irreversibly depending on the properties of the solid. Obviously, if the properties of the solid change because of temperature, strain rate or water absorption effects, these changes can be transmitted to the cellular structure. Such changes are particularly significant when the behaviour of the solid changes from brittle (crisp texture) to plastic or rubber-elastic (soggy texture) as a result of water pick-up.

Also important from the point of view of perceived texture of cellular foods are the rules which govern the propagation of damage initiated by the mechanisms discussed above. Texture is likely to be affected by damage stability considerations. It is perhaps possible to differentiate quantitatively between a crisp and a crunchy texture, associating the former with unstable propagation of brittle collapse and the latter with stable, progressive propagation.

At present little is known about these aspects but they are perhaps among the most relevant ones for a better understanding of texture as a sequence of damage initiation, development and propagation.

Conclusions

The application to food materials of experimental and theoretical methods of investigation such as those presented here is just beginning. Progress is slow because of the complexities involved in characterisation, testing and analysis, but the available methods developed for other materials must in principle be applicable to food structures as well. The