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On the structure and mechanical properties of beetle shells

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Rose chafer beetle shells are composites of chitin fibres and proteinaceous matrix in an orthogonal plywood-like laminate. Fibre layers are connected by unique inter- and intra-ply cross-links that afford a novel solution to shear- and crack-propagation resistance.

The elastic and plastic properties of both isolated fibres and the composite shell were investigated in terms of orientation and state of hydration. It appears that beetle shell design is based on attaining reasonable functional isotropy from an inherently tough anisotropic fibrous structure.

1. Introduction

Brittle fracture and fatigue failure are virtually unknown in bio-materials operating under normal biological conditions. This is amply illustrated by the hard shells of beetles which combine strength and flexibility into a remarkably tough material. In view of the geological age of beetles, their present structures reflect the sophisticated end-product of a great deal of "engineering experience" gained during the course of evolution. This suggests that beetle shells have successfully compensated for the basic anisotropy of their structural fibres and are well designed to meet particular engineering requirements, and invites the conjecture that biological materials may provide unique solutions to application problems of man-made fibre-composite materials.

It will be shown that beetle shells are structurally somewhat analogous to both plywoods and fibre-reinforced metal composites. It is of interest to determine whether beetle shells exhibit the same variations in elastic and plastic properties as do the above systems, and to compare the mechanical behaviour and fracture patterns of beetle shells with other composite materials.

2. Experimental methods

2.1. Materials

All of the data reported here are based on the shells of a rose chafer, *Pachynoda sinuata*, a member of the Scarab beetle family. Shell structure was optically determined from microtome sections and from aluminium-coated specimens viewed with a scanning electron microscope (SEM). The SEM specimens had to be vacuum freeze-dried prior to vacuum-coating to prevent shell collapse. Test specimens were obtained by cutting the ventral thoracic plates into 4 × 2.5 × 0.2 mm strips. The strips were taken in two patterns, one at 45° and the other at 90° to the longitudinal axis of the beetle. (Note: It is shown in Section 3.1 that the shells consist of orthogonally aligned plies such that each ply lies at 45° to the beetle's longitudinal axis. Therefore, a strip cut at 45° to this axis results in test specimens in which the plies alternate at 90°/0°. Strips cut at 90° to the beetle's axis result in specimens in which the plies are at +45°/−45°. Throughout the text 90°/0° refers to ply angles with respect to the stress axis and likewise for +45°/−45°). Samples of each orientation were hydrolyzed in concentrated potassium hydroxide to remove all matrix protein, leaving the fibres intact. Of these, some were oven-dried at 343 K for 48 h and held in sealed vials until needed, others were kept in de-ionized water at 293 K prior to testing.

The relative volumes of fibre and matrix were determined on a dry-weight basis by

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alkaline hydrolysis of the matrix proteins and found to be 47% fibre and 53% matrix. Volume fractions in insect shells are highly variable among different insects [1] and must be determined separately for each species.

2.2. Test conditions

Uniaxial tensile tests were performed at a strain-rate of approximately 4.4×10^{-4} sec^{-1}. The following sets of tests were made on both the 45° and the 90° specimens: fresh beetle shell at 77 and 293 K; wet fibres at 293 K; oven-dried fibres at 293 K. Fracture surfaces were observed directly with a small telescope during the tests and were further studied in a scanning electron microscope.

Shear moduli for beetle shell and wet chitin of 45° and 90° at 293 K, were measured by timing the frequency of torsional vibrations, as has been done for wood samples [2]. Approximate moduli are given by: $G = 12\pi^2 Il/(bd^3T^2)$ where I = moment of inertia of the oscillating disc, l = specimen length, b = specimen breadth d = specimen thickness, and T = period of torsional vibrations.

There is no technique available by which the matrix proteins can be obtained and studied directly. Matrix contributions to the composite can only be assessed circumspectly by observing differences in the behaviour of isolated fibres and intact shell plates.

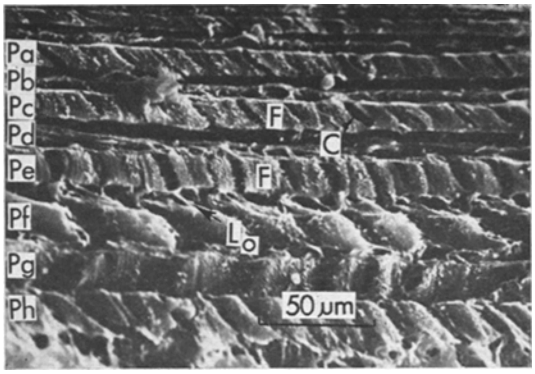

Figure 1 Cross-section of multi-ply laminate beetle shell.

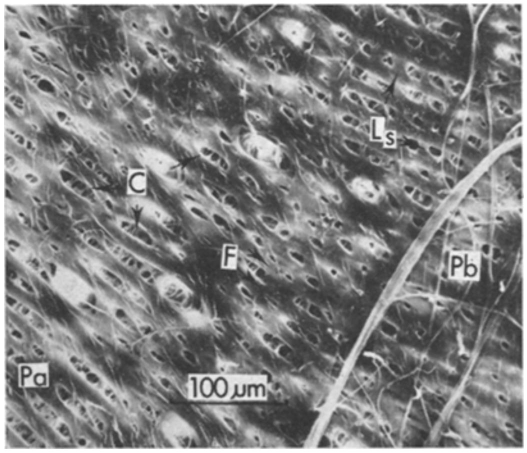

Figure 2 Surface of a single macrofibrillar layer of isolated dry chitin.

3. Results

3.1. Shell structure

The shells are composed of chitin fibres embedded in a protein matrix. Chitin (poly-*N*-acetyl-*D*-glucosamine) is the structural polymer of all insects and some other lower organisms [3]. The fibres occur as ~ 30 nm diameter *microfibrils* grouped in non-twisted, rectangular and parallel *macrofibrils* of ~ 100 square microns cross-section. The parallel macrofibrils form layers or sheets as in plywoods (P in Figs. 1 and 4). However, the macrofibrils of a layer are not discrete, as floor planks, but are connected by numerous intra-ply cross-linking fibrils (L_s in Fig. 2). Between the linking fibrils are pore canals which traverse the entire shell (C in Figs. 1 and 2) and allow for chemical transport within the shell and access to its surface [4]. Thus, a single layer of macrofibrils is effectively an expanded linear mesh (Fig. 2).

Adjacent macrofibril layers usually cross each other orthogonally, but the outer series of layers may be out of angle phase with the lower layers (Fig. 1). Neighbouring layers are interconnected by inter-ply linking fibrils (L_o in Fig. 3). The total number of layers varies in different parts of the shell depending upon the animal's structural needs [5]. The orthogonal layers are aligned at 45° to the longitudinal axis of the beetle. A typical complete shell region of fourteen layers is ~ 200 µm thick and is covered by a thin, ~ 2 µm, very brittle water-proofing layer (E in Figs. 5 and 6, [6]). Although a clear picture of the matrix proteins is still wanting, it is known that the fibre-matrix composite shell is chemically stabilized by quinone and polyphenol tanning of the shell [7].

3.2. Mechanical properties

3.2.1. Tensile

The elastic strains (ϵ_e) of all specimens are of the order of $2\frac{1}{2}$ to $3\frac{1}{2}$%; however, the plastic

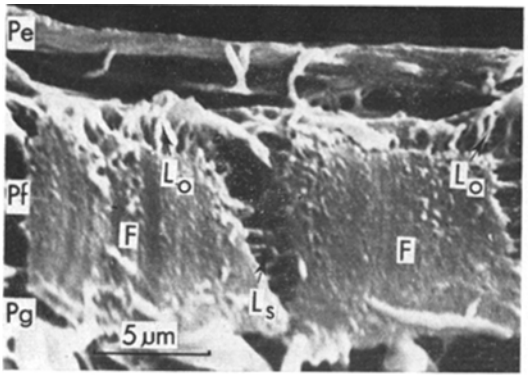

Figure 3 Intra- and inter-ply cross-linking fibrils between macrofibrils.

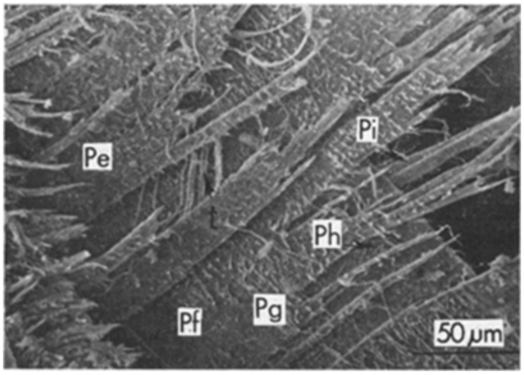

Figure 4 Detail of fractured shell indicating torn macrofibril.

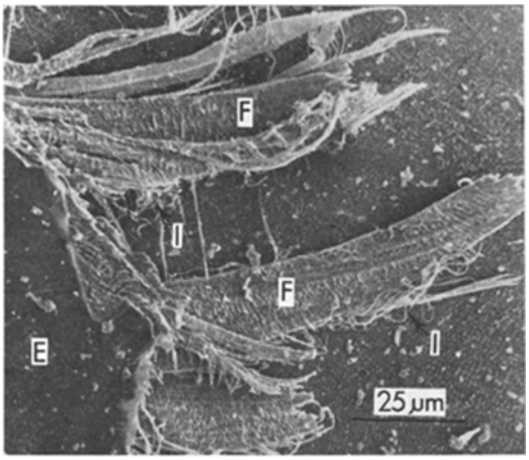

Figure 5 Detail of fractured shell indicating waterproofing layer and microfibrils.

strains (ϵ_p) vary, reaching 20% in beetle shells and wet chitin at the 90°/0° angle orientation (Table I, Figs. 7 and 8). Isolated chitin is

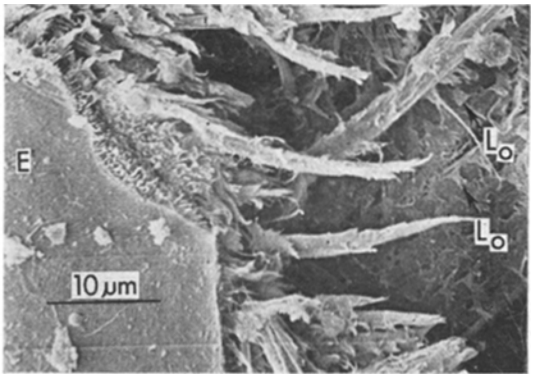

Figure 6 Shear failure of inter-ply linking fibrils.

stronger at 90°/0° than +45°/−45° and shows more pronounced orientation effects in the wet than in the dry condition (Fig. 7). Total elongation of chitin does not show a large orientation dependence. Beetle shells show different behaviour at room temperature in that the stress at the elastic limit (σ_e) and the maximum stress (σ_{max}) for the +45°/−45° orientation are almost twice that of the 90°/0°. Total elongation at 90°/0° is far in excess of that at +45°/−45° (Table I, Fig. 8).

The importance of water in the mechanical behaviour of these materials is shown by the following: (a) dry chitin is less plastic than wet; (b) beetle shell is of lower modulus and strength than dry chitin; and (c) beetle shell and wet chitin are ductile while beetle shell at 77 K and dry chitin are brittle. These results are consistent with the theory that the elasticity and plasticity of the wet fibres depend upon the slipping of hydroxyl inter-chain bonds mediated by water lubrication [8, 9].

The differences in behaviour of beetle shell and isolated chitin reflect protein matrix effects. The ratios of the values of σ_e, E, and σ_{max} for beetle shell to the corresponding values for wet chitin at 90°/0° are respectively 1.23, 1.42 and 1.39, and the plastic strains for these specimens are the same. Therefore, there is little fibre/matrix interaction at this orientation. In contrast, matrix effects are clearly seen in the +45°/−45° specimens where the corresponding ratios are 4.8, 3.2 and 3.3 and the plastic strain for wet chitin is more than twice that of beetle shell (Table I, Figs. 7 and 8). In the case of torsion, the influence of matrix is even more apparent (see Section 3.2.2).

Observations on the fracturing surfaces during

TABLE I Mechanical properties of whole beetle shells and isolated chitin

Specimen	σ_e(MN m^{-2})	ϵ_e	E(MN m^{-2})	σ_{max}(MN m^{-2})	ϵ_p
Wet chitin 90° 293 K	22	0.035	630	26	0.2
Wet chitin 45° 293 K	12	0.025	480	18	0.16
Dry chitin 90° 293 K	75	0.026	2900	80	0.06
Dry chitin 45° 293 K	70	0.025	2800	75	0.06
Beetle shell 90° 293 K	27	0.03	900	36	0.2
Beetle shell 45° 293 K	58	0.038	1520	69	0.07
Beetle shell 90° 77 K	75	0.032	2350	92	0.03
Beetle shell 45° 77 K	85	0.035	2420	110	0.02

testing, revealed that failure of the +45°/−45° specimens occurred by shear parallel to the macrofibril axes while in the 90°/0° specimens fractures were normal to the tensile axes (Figs. 9 and 10). In addition, failure of the composite shell is a step-wise process in which the thin, brittle outer water-proofing layer fails first, followed by the more brittle outer layers and finally the softer inner layers of the shell. Although the inter-ply angle has been observed to gradually decrease during deformation of wet chitin +45°/−45° specimens, allowing the layers of macrofibrils to become more parallel to the tensile axis [5], this movement contributes little to strain as the 90°/0° specimens are similar to the +45°/−45° elastically, and the plastic strain for the 90°/0° generally exceeds that of the +45°/−45° specimens.

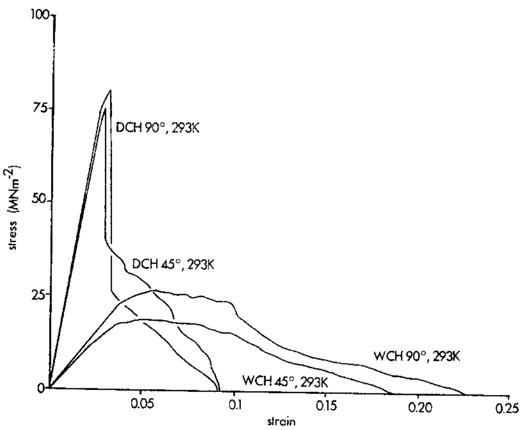

Figure 7 Stress-strain curves for wet and dry chitin of +45°/−45° and 90°/0° at 293 K.

3.2.2. Torsional rigidity

The values of shear modulus obtained by the torsional vibration technique are only approximate since the equation used assumes an isotropic material. In addition, since the shear modulus is inversely proportional to the cube of specimen thickness and the thickness values are inaccurate because of variation along individual specimens, these data show a large scatter. This scatter would be sufficient to mask any possible differences in rigidity due to orientation. However, chitin and beetle shell differ without regard to orientation as follows: beetle shell- 150 to 600 MN m^{-2}, chitin - 30×10^6 MN m^{-2}. Thus, the role of the protein matrix in resisting shear is evident, since the ratio of shear modulus to Young's modulus for beetle shells is at least twice that for isolated wet chitin.

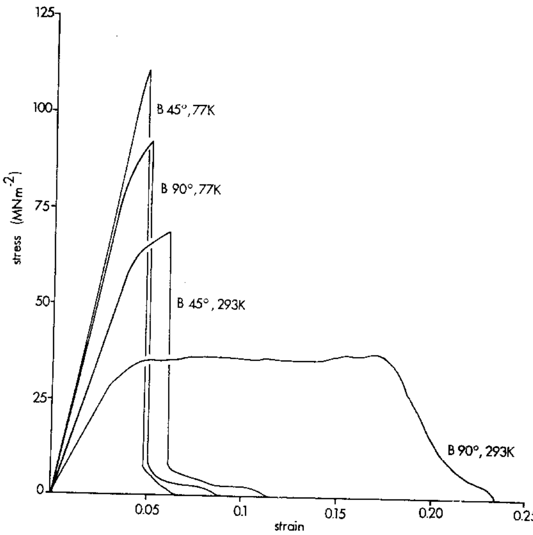

Figure 8 Stress-strain curves for beetle shells of +45°/−45° and 90°/0° at 77 and 293 K.

4. Discussion

The macrostructure of beetle shell is analogous to plywood and the individual fibres are reminiscent of the fibrillar structure of wood itself [10]. Functional similarities between beetle shells, plywoods and other engineering materials are discussed below.

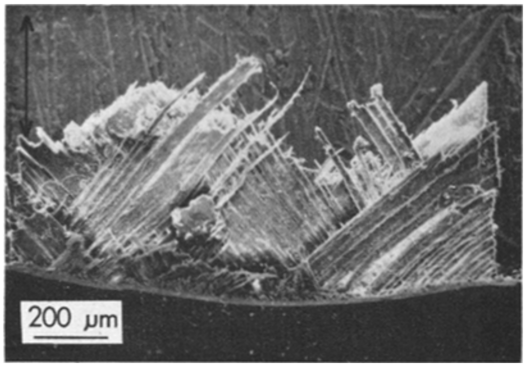

Figure 9 Typical shear failure of beetle shell of the $+45°/-45°$ angle orientation.

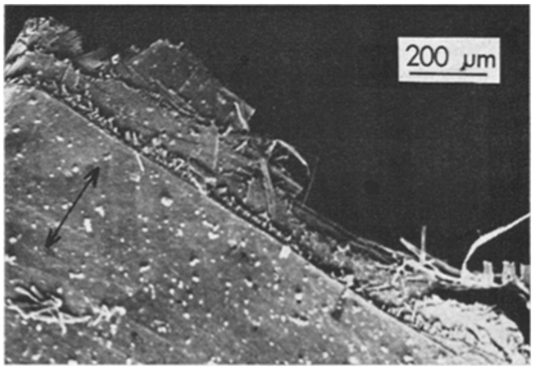

Figure 10 Typical failure of beetle shell of the $90°/0°$ angle orientation normal to stress axis.

4.1. Crack-stopping
Toughness or resistance to crack propagation in fibrous materials is due to the crack-blunting action of the matrix. The stresses at the crack tip can be reduced plastically, or the tensile stress normal to the fibre axis may be sufficient to produce a longitudinal crack and thus reduce stress-intensity enough to stop any lateral growth of the crack. The fibrous structure of beetle shells is ideal for blunting cracks in this manner. Figs. 9 and 10 show extensive interface failure which has thus toughened the shell. The presence of the cross-linking fibrils will not decrease the shell's ability to blunt cracks in this manner.

4.2. Orientation
The tensile strength of a composite σ_c along the fibre axis is largely determined by the intrinsic strength of the fibres σ_f and their volume fraction V_f such that $\sigma_c = \sigma_f V_f + \sigma_m'(1 - V_f)$ where σ_m' is the tensile stress carried by the soft matrix when the composite is strained to its ultimate tensile strength. Maximum fibre-volume fraction in the beetle shell has been attained by constructing the macrofibrils of rectangular cross-section (Figs. 1 and 3). In this way, as in the case of wood, the strength of the fibrous sheets has been optimized in a manner not frequently encountered in man-made materials.

A single sheet of aligned fibres fails in shear parallel to the fibres when a tensile stress is applied at an angle θ greater than about $10°$ to the fibre axes [11]. Tensile strength decreases according to $\sigma_\theta\ \tau/(\sin\theta\cos\theta)$ where τ = failure stress of the matrix in shear or of the fibre matrix interface. Experiments on continuous fibre sheets have shown that the tensile strength can be reduced by as much as 90% as the angle to the fibre axis increases [11]. However, for bonded laminates of $+45°/-45°$ orientation, the shear parallel to the fibres of one sheet is opposed by the oppositely-arranged neighbouring sheets. Experimental results for cross-plied laminates of reinforced plastics show that tensile strength is reduced by a factor of only 50% in the $+45°/-45°$ arrangement [12]. It should be noted that the bonding together of aligned fibrous sheets in different directions confers greater isotropic strength than randomly-arranged fibres since a much larger volume fraction can be obtained in the aligned sheet method.

The success of bonded laminates of fibrous materials in resisting shear depends upon the strength of the fibre/matrix bond and the adhesion between layers. Since beetle specimens of the $+45°/-45°$ orientation fail by shear parallel to the fibres (Fig. 9) and σ_e, E, and σ_{max} are all in excess of those quantities for the $90°/0°$ specimens (in contrast to synthetic composites), it is obvious that beetle shell is designed to resist shear deformation. The presence of the inter- and intra- ply linking fibrils must contribute to the material's shear resistance, but the fact that wet chitin is stronger in the $90°/0°$ orientation shows that the chitin/protein interface is extremely strong and is critical to shear resistance.

4.3. Bending, twisting, and fatigue
Orthotropic fibrous materials, like wood, are of rhombic symmetry and exhibit an interdependence of elastic constants [13]. For example, if a sheet of wood cut at 45° to the grain is subjected to a torque, it will bend and twist. Likewise, an applied bending stress both bends and twists.

If the sign of the angle with respect to the axis of twist is changed, the resulting bending is reversed. Plywood construction employs these opposing reactions with the result that these laminates have a maximum shear-modulus at 45°. It is apparent that beetle shells benefit from the same design considerations in order to resist shear distortions associated with torque during flight [14].

Studies of man-made fibre-composite materials have shown that the fatigue life in cyclic tensile loading is far greater than for non-tensile loading. The application of cyclic bending or twisting loads results in inter-laminar fatigue failure because flexure of a laminated structure generates high stresses on the weak inter-laminar planes. The occurrence of inter-laminar cracking in bending, especially cyclic bending, in man-made fibre-composite materials is common unless the fibre/matrix bond strength is high. Inter-laminar weakness would be a serious disadvantage in the case of beetles since the thoracic box itself must repeatedly change in shape to maintain continuity of wing stroke during flight [14].

Assuming that the thoracic box is only stressed at the same frequency as the wing stroke, then the fatigue life of the shell must reach values of at least 10^7 cycles. This is based on an average life span of 180 days of which about 13% is actual flying time. If the laminated shell is to survive then some unique structural design might be anticipated. It would appear that the beetle does not solely rely on the strength of the fibre/matrix bond, but also uses the inter-ply fibrils (Figs. 3, 4 and 6) in order to prevent inter-laminar cracking and fatigue failure. It is also apparent that the occurrence of the $+45°/-45°$ply orientation with respect to the animal's longitudinal axis is ideal in resisting excessive cross-sectional shape changes during flight.

The static tensile-strength of beetle shell is of the same order as leather, rope, tendon, wood and other structural bio-polymers [15], and the moduli do not exceed those of wood or un-reinforced plastics. Beetle shells appear more concerned with attaining reasonable isotropy from inherently tough anisotropic fibres and resisting torsional fatigue.

Acknowledgements

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