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Fracture toughness and damage development in limpet shells

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ABSTRACT

Fracture toughness is an important property for many biological materials, but it can be difficult to obtain accurate and relevant values of toughness in such materials owing to complexities of geometry, material anisotropy, etc. Here we present the results of the first ever attempt to describe and measure cracking and fracture toughness in the shells of limpets. Three different experiments were devised. Firstly, small single-edge-notched bend specimens were machined, enabling us to measure K_{IC} for through-thickness cracks growing in the circumferential direction in the shell walls, giving a value of 0.98 MPa√m. Secondly, radial notches were cut into intact shells which were loaded in compression through the apex. Failure occurred by crack propagation from the notch roots, and finite element analysis (FEA) was used to obtain critical K values. However the analysis gave a surprisingly high toughness value and the results were very sensitive to test variables, especially friction. The experiment demonstrated the remarkable resistance of shells to this kind of damage, but could not be used to measure $K_{IC.}$ Thirdly, impact tests were carried out to create internal damage in the form of delamination cracks. This allowed us to estimate toughness in terms of a crack propagation energy G_{IC} for these cracks of 146 J/m^2, equivalent to a K_{IC} of 2.59 MPa√m. Scanning electron microscopy showed that the delamination cracks had much smoother fracture surfaces than those from the through-thickness cracks, however they displayed a regular structure of folds or pleats at the 100 nm scale which may act to hinder crack face movements during shear/compression loading as occurs under impact, which is a common cause of damage for these shells in their natural surroundings.

1. Introduction

Many biological materials fail by brittle fracture in which crack-like defects propagate: examples are bone, skin and wood. This suggests that fracture toughness is an important property in determining their structural integrity. Previous workers have studied toughness and crack propagation in various natural materials, to develop better understanding of their structure/function relationships, and also to provide inspiration for the development of fracture-resistant engineering materials. Examples of previously studied materials include bone [1], cartilage [2], wood [3], eggshell [4] and insect cuticle [5]. The shells of molluscs and other marine animals have also been studied, including abalone [6], mussel [7] and conch [8]. These shells all consist of calcium carbonate plus a few percent organic material, but large differences in toughness have been found. Nacre, which constitutes one of the layers in the abalone shell, has been shown to have remarkably high toughness [9] and this had led to much biomimetic work to develop new high-toughness ceramics (e.g. [10]).

Up to now, fracture toughness has not been measured in limpet shells. Limpets live in intertidal zones in many parts of the world, being very abundant and including many different species. A significant cause of death for these animals is damage to the shell caused by impacts from moving rocks and other objects during storms [11,12]. Cracks and holes thus created may result in death by dehydration or predator attack, but limpets do have some ability to repair this damage [11]. Previously we showed that the mechanism of failure during impact is internal delamination [13]. Limpet shells consist of several layers which are laid down approximately parallel to the shell surface [14] (see Fig. 1). Impacts applied by dropping weights on the shell apex caused cracks to form on the interfaces between these layers, leading to layer separation and loss of material by spalling [13]. Another failure mode, infrequent in our work but reported as dominant in other limpet species [12], is the initiation of cracks at the shell rim and their propagation in radial and circumferential directions.

As pointed out in a recent review [15], the determination of fracture toughness for biological materials presents some particular challenges. In principle one can use approaches which are well known in the characterisation of engineering materials. Two toughness parameters

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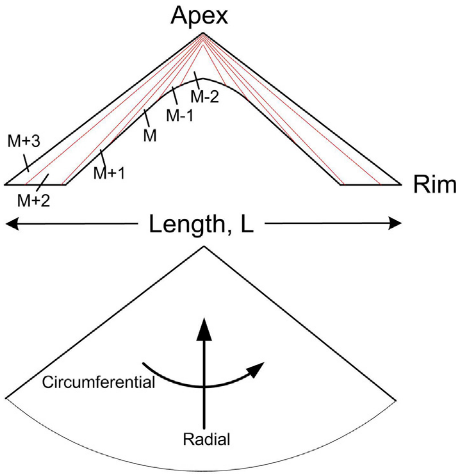

Fig. 1. Definition of the terms “apex” and “rim” and the directions “circumferential” and “radial”, with respect to the limpet shell. Also shown (in schematic form) is the typical layered structure of these shells, with layers denoted M, M + 1, M − 1, etc. (adapted from Ortiz et al. [14]).

can be defined: G_c (which we will refer to as the crack propagation energy) is the amount of energy required to increase the area of the crack by a given amount, measured in J/m^2, and; K_c (the fracture toughness) allows one to calculate the stress required to cause a crack of a given length to propagate, leading to a brittle fracture. The materials concerned are almost always anisotropic and often they are available in sizes and shapes which make it difficult or impossible to obtain conventional test specimens. The aim of the present work was to determine the fracture toughness of limpet shell material, considering three different cases: through thickness cracks propagating in the radial and circumferential directions, and delamination cracks propagating between the layers within the shell thickness.

2. Methods and materials

The limpet species *Patella vulgata* (Linnaeus 1758) was chosen for study as it is present in large numbers on the coast near Dublin. Shells were obtained from living animals; using a knife it was possible to prise the shells intact and undamaged from the rocks to which they were attached. Three different experiments were devised, as illustrated schematically in Fig. 2.

2.1. Experiment 1: Circumferential propagation of through-thickness cracks

Rectangular samples of nominal dimensions 20 × 5 × 2 mm were cut and machined from the wall of the shell in the orientation shown in Fig. 2. Seven specimens were tested. Actual dimensions varied slightly and were measured using a micrometer and Vernier calipers. A sharp crack-like notch was introduced through-thickness by cutting with a fine-bladed saw and sharpening the tip with a scalpel, creating crack-like notches with root radii of approximately 5 μm and lengths (a) varying from 0.6 mm to 1 mm. These specimens were treated as conventional SENB type (single edge notched bend), loaded in three-point bend in an Instron testing machine. A typical load/displacement trace is shown in Fig. 2, indicating a clear load drop on crack propagation, which was used to calculate the fracture toughness K_C using the standard formula for a load P applied to a sample of width W, thickness B, loading span S (from ASTM E-399-83):

$$K_C = F(a/W)PS/(BW^{3/2}) \tag{1}$$

where $F(a/W) = 1.5(a/W)^{0.5}[1.99 - (a/W)(1 - (a/W))\{2.15\text{–}3.93((a/W) + 2.7(a/W)^2\}](1 + 2(a/W))^{-1}(1 - (a/W))^{-3/2}$.

2.2. Experiment 2: Radial propagation of through-thickness cracks

Intact shells were used in this experiment, tested in axial compression between steel platens (lubricated with WD40) as shown in Fig. 2. Shell rims were typically quite uneven because in the natural state they grow to conform to the rock surface. Initial experiments showed that failure tended to occur due to local stress concentrations where the rim made contact with the steel platen, so all test specimens were ground flat using silicon carbide paper. A radial notch of length 6 mm was cut in each specimen, starting at the rim, using a saw and finishing with a scalpel as in Experiment 1. Nine specimens were tested. The average rim diameter was 30.25 mm (varying from 28.5 mm to 32.5 mm). As the load trace in Fig. 2 shows, failure was associated with a sudden drop in load. For comparison purposes, a further 9 samples of similar size (varying from 26 mm to 34 mm) were tested in the same way, but without introducing a notch. A simple test was carried out to estimate the friction coefficient μ between the shell rim and the lubricated steel platen. The platen was inclined to find the angle to the horizontal at which the shell began to slide under its own weight. The value of μ is given by the tangent of this angle.

To determine the stress intensity K for this type of specimen a finite element model was created using commercial software (ANSYS Workbench 18.0). Fig. 3 shows the model and examples of results. The model was intended as a simplified version illustrating the main features of the limpet shell. It has a circular rim, whereas actual limpet shells are slightly oval in shape, and we did not include the radial ridges which are a feature of the outer surface of these shells. The outer diameter at the rim was chosen to be the same as the average experimental value (30.25 mm), whilst the height at the apex (11.88 mm) and shell wall thickness (1.29 mm except at the apex where it increases to 2.58 mm) were chosen based on published geometric data for this species [16]. A radial crack of length 6 mm (root radius zero) was included. Since the model is circular we took advantage of symmetry to model one quarter of the shell: the crack was modelled by applying boundary conditions to create a free surface over the area where the crack exists.

The mesh consisted of tetrahedral elements in most of the model, of a size sufficient to obtain three elements through thickness (which was sufficient to converge global measures such as deflection under load). In the vicinity of the crack hexahedral elements were used and the element size was refined to achieve convergence of the stress intensity result (K). The material was assumed to have a Young's modulus of 46GPa and Poisson's ratio of 0.2, based on data from the literature [17]; anisotropy of elastic modulus was not modelled for lack of information (Note: the value actually given for Patella vulgata in this source is 18GPa, however this is very much lower than all other values for related species as measured by this author, so we decided to use the average of all values for gastropod shells in this paper). Various contact states between rim and platen were considered, including fully bonded contact, and sliding with varying degrees of friction.

2.3. Experiment 3: Delamination cracking during impact testing

Impact testing was performed by placing the shell on a flat surface and dropping a cylindrical steel weight (mass 123 g, diameter 20 mm, length 50 mm) from a given height. In a previous study [13] we determined that the energy to cause failure was proportional to the shell's maximum diameter L to the power 4.6; the normalised impact strength was found to be 8.8 MJ/m$^{4.6}$. In the present work we applied impacts equal to 10% of this value to 10 shells and impacts of 20% to a further 10 shells. The shells were then cut and polished to reveal a vertical section as shown in Fig. 2. Silicon carbide papers and diamond-impregnated cloths were used, of varying roughness down to a 1 μm finish, allowing us to observe cracks in the material. Most observations were made using optical microscopy but some scanning-electron microscopy was carried out to confirm that the features being observed