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ScienceDirect
Procedia Structural Integrity 2 (2016) 042–049
Structural Integrity Procedia
www.elsevier.com/locate/procedia

21st European Conference on Fracture, ECF21, 20-24 June 2016, Catania, Italy

Fracture Mechanics in Biology and Medicine

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Abstract

Many biological materials have load-bearing functions: examples include bone, cartilage, wood, insect cuticle and eggshell. These materials have evolved into structures such as skeletal parts, wings, plant stems and shells. This paper presents examples of research investigating failure at both the material level (where crack initiation and propagation is a common fracture mechanism) and the structural level, where competing failure mechanisms exist such as buckling, splitting and fatigue.

The study of these fracture problems from nature is interesting and rewarding of itself, to increase our knowledge of the world around us. But it also has two important practical applications. Firstly, new materials and structures can be developed by mimicking Nature's solutions. One example is the development of tough materials arising from the study of nacre, conch shells and other natural materials based on calcium carbonate. These materials have achieved increases in fracture toughness of more than an order of magnitude by the use of toughening micromechanisms. Secondly, improved medical treatments and diagnostic procedures arise from the study of bone and soft tissues in the body, contributing to the understanding and prevention of stress fractures, osteoarthritis and other debilitating conditions.

There is an important role here for those of us who have expertise in fracture mechanics and structural integrity, to apply the lessons learnt from engineering materials, to biological materials, and *vice versa*.

Peer-review under responsibility of the Scientific Committee of ECF21.

Keywords: Fracture mechanics; biology; medicine; toughness; eggshell; cuticle; buckling; biomimetics

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10.1016/j.prostr.2016.06.006

1. Introduction

Fracture mechanics is a relatively young science: we are still working to understand concepts such as the nature of toughness, the role of microstructure in determining toughness, and the interaction of failure modes in structures, such as cracking, yielding and buckling. In our work we can take inspiration from Nature, where we find many examples of toughening mechanisms operating at different length scales and the evolution of structures with good – in some cases optimal – strength to weight ratios, equipped to resist several competing failure mechanisms. In this paper I describe some of the recent work carried out in my laboratory. Our aim is to study as wide a variety of natural, biological materials as possible, applying the engineering techniques of failure analysis, fracture mechanics and structural integrity to help understand how these materials fulfill their functions in many different types of animals and plants. For illustration purposes I will focus on three examples. The first example is concerned with the fracture toughness of eggshell, the development of a novel method to measure this property and its value discussed in the context of other calcium carbonate materials in nature which display different toughness values as a result of various toughening mechanisms at the microstructural level. The second example is concerned with crack propagation in the skeletons of animals and the ability of living systems to detect and repair damage. The third example considers a leg segment – the tibia of an insect - as an example of an optimized structure taking account of two competing failure modes.

2. Fracture toughness and toughening mechanisms in nature: eggshell and related materials

2.1. Background

It is immediately evident to anyone with understanding of the concept of toughness that the shells of eggs are made from a very brittle material. But how brittle exactly? Surprisingly, there have been very few previous publications on the measurement of fracture toughness (K_c or G_c) in eggshell, and all of these previous studies have resulted in incorrect values. Mabe *et al* (2003) reported values of K_c for typical hen's eggs of the order of 11MPa√m. This value was arrived at by compressing whole eggs between parallel metal platens until failure occurred: a formula was quoted in the paper, expressing K_c in terms of the failure load and egg dimensions. As far as I can discover, there is no derivation of this formula in any published paper. In principle it should be possible to deduce toughness from this type of test, because failure occurs by the propagation of cracks which initiate at the contact points, so the problem is somewhat similar to that of the cracking of a brittle material during an indentation test. Macleod *et al* (2006) developed the mechanics of this phenomenon in considerable detail, though they stopped short of actually estimating toughness by this approach.

Anyone with a knowledge of the fracture toughness of materials will immediately realise that the above value of 11MPa√m is much too high to be correct. Eggshell is a ceramic material consisting of calcium carbonate crystals plus a small amount of organic material (various natural polymers). There are almost no ceramic materials with K_c values greater than 10MPa√m. Furthermore, a simple calculation based on knowledge of the tensile strength of eggshell would deduce that, given this value of K_c, the critical crack length would be larger than the size of an egg, implying that eggs will never break by cracking. What is even more worrying is that the work of Mabe *et al* has been duplicated by other workers: Xiao *et al* (2014) used the same approach, with the same equation (though slightly misquoted in the paper) and obtained similar results, with an average of 12.6MPa√m.

The only other paper which I could find on this subject was by Gosler *et al* (2011) who measured G_c in the eggs of the Great Tit by measuring the energy to cut samples using a scissors. Their results were very varied (0.5-17kJ/m^2): when converted to K_c these give values of the same order of magnitude as above. So we can conclude that, up to now, there have been no reliable measurements made of the fracture toughness of eggshell. This is really remarkable considering the importance of eggs, and the fact that small cracks formed during their handling and transport are responsible for considerable wastage of the product and also give rise to health risks.

2.2. A novel approach to toughness measurement

To fill this gap, we devised a novel way to measure fracture toughness (Taylor *et al* 2016). The test rig is illustrated in figure 1. It is based on the principle that if a thin walled hollow sphere is compressed along its poles, a very simple state of stress arises at locations remote from the loading points. Bending is prevented, leaving a biaxial membrane stress consisting of a compressive stress normal to an equal and opposite tensile stress. It is the tensile stress, which acts in the circumferential direction around the equator of the sphere, which is of interest here. At the equator this stress has a magnitude given by (for an applied force F, sphere radius b and thickness t):

$$\sigma = \frac{F}{2\pi bt} \quad (1)$$

Our method involves placing a notch in this region, as shown in figure 1, such that the above tensile stress causes brittle fracture from the notch. To prevent failure occurring near the loading points we used hemispherical cups and layers of foam to distribute the applied force. We tested notches with different root radii and extrapolated the results to zero root radius to estimate the effect of a sharp crack: root radii less than about 0.1mm gave results very similar to the sharp crack estimate.

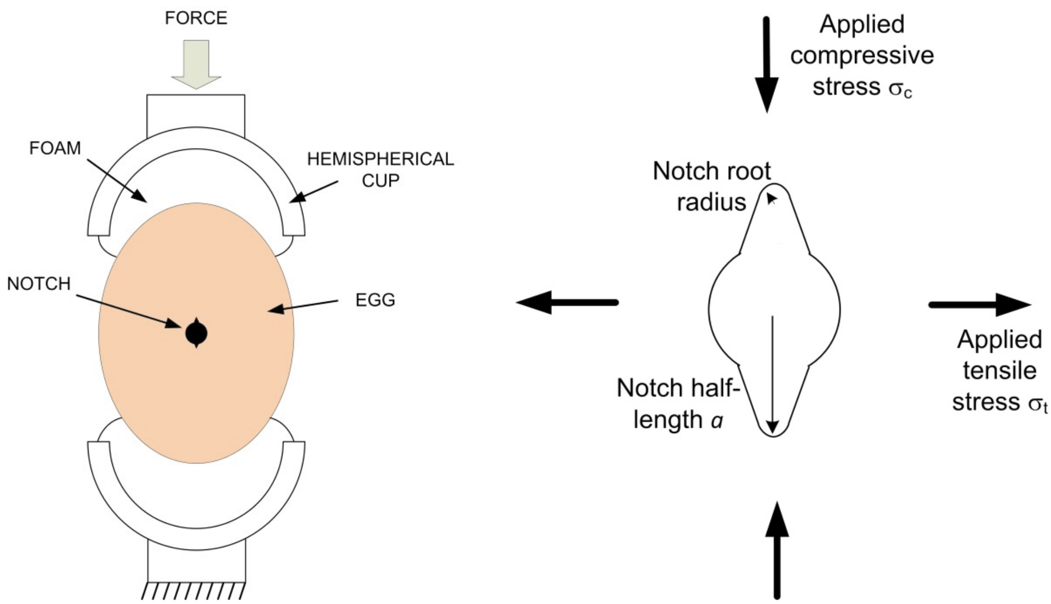

Fig.1. Schematic illustration of the test rig (on the left) and the biaxial stress state near the notch (on the right)

2.3. Eggshell toughness results and their significance

Using this approach we obtained a value for the fracture toughness K_c of 0.3MPa√m. It is interesting to discuss this value in the context of the values already measured for related natural materials. The mineral which makes up the great majority of eggshell is $CaCO_3$ in the calcite form. Geological mineral calcite has a toughness of about 0.2 MPa√m. Many organisms, especially shellfish of various kinds, have shells made from calcite, or the related form aragonite. Examples are mussels, conch shells and nacre, which is the material found in oysters and often called "mother of pearl". These materials have fracture toughness values which are an order of magnitude higher, in the range 3-5 MPa√m. All of these biological forms, including eggshell, have essentially the same composition, with just a few percent of organic material, so how does this large variation in toughness come about? Recent research has shown that several toughening mechanisms operate as a result of structure at a scale of the order of microns and, in some cases, even smaller (Currey et al 2001, Barthelat et al 2007). Nacre, for example, has a brick-like structure in which individual ceramic units are separated by very thin layers of organic polymer. This creates a lot of weak interfaces which delaminate ahead of the main crack, using up energy, and also cause extensive crack deflection, as shown in figure 2. Other toughening mechanisms which have been identified include crack deflection at twin boundaries within calcium carbonate crystals in the conch shell. By contrast, our work showed that these mechanisms are not active in eggshell. As figure 2 shows, cracks in this material are very straight, showing little deflection or branching, Examination of fracture surfaces showed large facets made up of multiple individual cleavage planes on the micron scale, mostly having low angle relationships to each other and therefore not inducing crack deflection.

This explains why the toughness of eggshell is so low, only slightly higher than that of pure mineral calcite. And for the chicken, this is a very good thing. The egg needs to be relatively stiff to prevent deformation when the mother bird is sitting on the egg, but then during hatching the young chick needs to be able to break the shell, which it does with its beak, making a small hole and enlarging it, causing failure by brittle fracture. So the correct specification for this material is one which has a high Young's modulus and a low fracture toughness, and indeed it turns out that eggshell has one of the highest ratios of E/K_c of any material, natural or manmade.

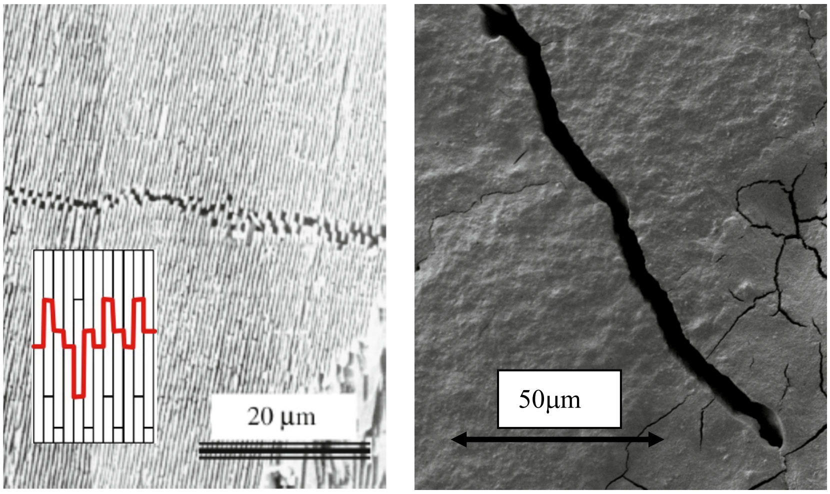

Fig.2. The photograph on the left shows crack propagation in nacre (Currey *et al* 2001); the crack path is illustrated schematically in the inset. The photograph on the right shows crack propagation in eggshell, from our work (Taylor *et al* 2016).

2.4. Consequences for medicine and engineering

This kind of work has also been done for another material system, and one which is of more immediate concern to human beings: the hydroxyapatite/collagen system which is present in various mammalian tissues such as bone, tooth enamel and dentin, as well as the antlers of deer. Previous work by ourselves and others (e.g. Nalla *et al* 2004) has shown that, just as in the calcium carbonate based system described above, one can identify a series of increasing toughness, from pure crystals of the ceramic phase (K_c = 0.5MPa√m) through enamel, dentin, bone and finally antler, which display increased toughness values up to about 5 MPa√m. Changes in microstructure are responsible, as well as increasing amounts of the polymeric phase, which leads to decreased hardness in the same sequence. In bone, fibrous features at the 100-micron scale (osteons, and in particular their boundaries) have a strong role in causing crack arrest and deflection. These findings are clearly of considerable medical importance. For example, changes in the microstructure and mineral content of bone are linked to diseases such as osteoporosis, so-called "brittle bone disease", which is highly debilitating.

Another very exciting development arising from studies of this kind is the creation of new materials, through the concept of biomimetics. There is much interest in making new ceramic/polymer composites based on natural structures such as nacre, using advanced manufacturing techniques such as 3D printing. In the last few years there has been a real explosion in the quantity and quality of this work, whereby some very significant increases in toughness have been achieved.

3. Crack propagation and repair in bones

The bones of animals are ceramic/polymer composites; they are essentially brittle materials with low K_c values. The principal failure modes during normal use are fatigue crack propagation and brittle fracture. So the fracture mechanics concepts which we use in engineering are very much applicable to improve our understanding of the function of the skeleton. This applies not only to the skeletal material of humans and other mammals, but also to the exoskeletons of arthropods such as insects. One very exciting aspect of skeletal material is its capacity for self repair. There has been a lot of work done by ourselves and others to understand how fatigue microcracks develop in bone and how they are being continuously repaired by systems of living cells (Taylor *et al* 2007). This work has been valuable in areas such as sports medicine, where better predictive models can prevent stress fractures in athletes, and also in the detection and treatment of osteoporosis and other bone diseases in which bone becomes less capable of self repair.

By contrast, there has been very little research done on cracking and repair in other organisms, including both animals and plants. Recently, we published the first biomechanical study of damage repair in the exoskeleton of an arthropod (Parle *et al* 2016). We introduced sharp notches into the legs of locusts, with a scalpel. By conducting cantilever bending tests we measured the fracture toughness of the material (which is called cuticle) to be 4.1MPa√m and showed that it decreased to 2.1MPa√m when the cuticle (which normally contains a significant amount of water) was allowed to dry out.

We then introduced similar notches into the legs of living insects. We found that after a period of three weeks or more the K_c value had apparently increased to 7.0MPa√m (see figure 3).

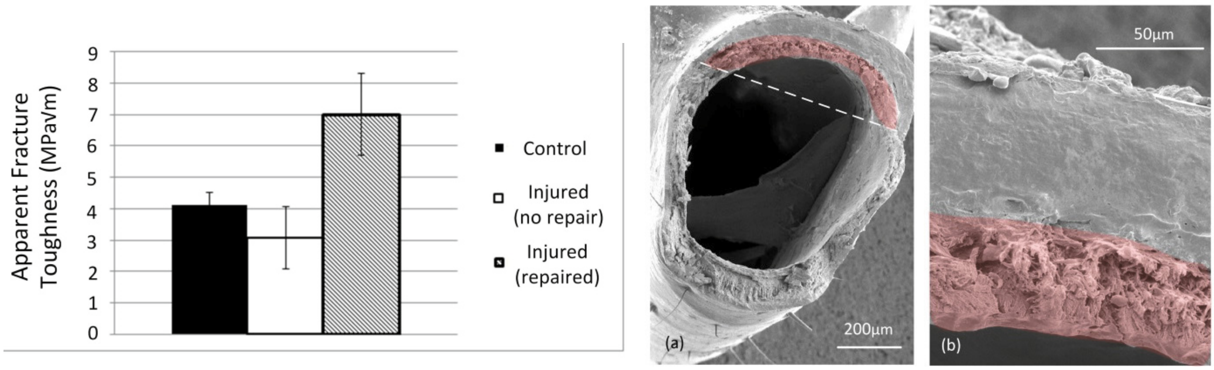

Fig.3. Apparent fracture toughness of insect cuticle after injury (a sharp notch) and repair. "Control" indicates tests results from material removed from the insect: "Injured (no repair)" refers to insects which did not form an endocuticle patch. The photographs show SEM images of fracture surfaces. The cut surface of the notch is at the top: highlighted in pink colour is the fracture surface of the endocuticle patch.

Further examination showed that this was not due to any change in the material itself, but rather caused by the formation of a new layer of cuticle, which had been deposited on the inside of the tube. Figure 3 shows a fracture surface in which the original cut notch can be seen along with this new material, which is called endocuticle. We were able to prove by further experiments that the deposition of this endocuticle was triggered by the damage which we had introduced, and was deposited preferentially in the area near the notch.

We used finite element analysis to study this repair process (see figure 4). By modelling the cut and also the new endocuticle layer we predicted that this layer should reduce the stress intensity K by a factor of 3.3, which was somewhat larger than the increase in K_c measured experimentally. The reason for this difference is most likely that failure occurs first in the patch of endocuticle, when it reaches its tensile strength, after which it is no longer able to protect the damaged area. Figure 4 shows the highly stressed material in the patch.

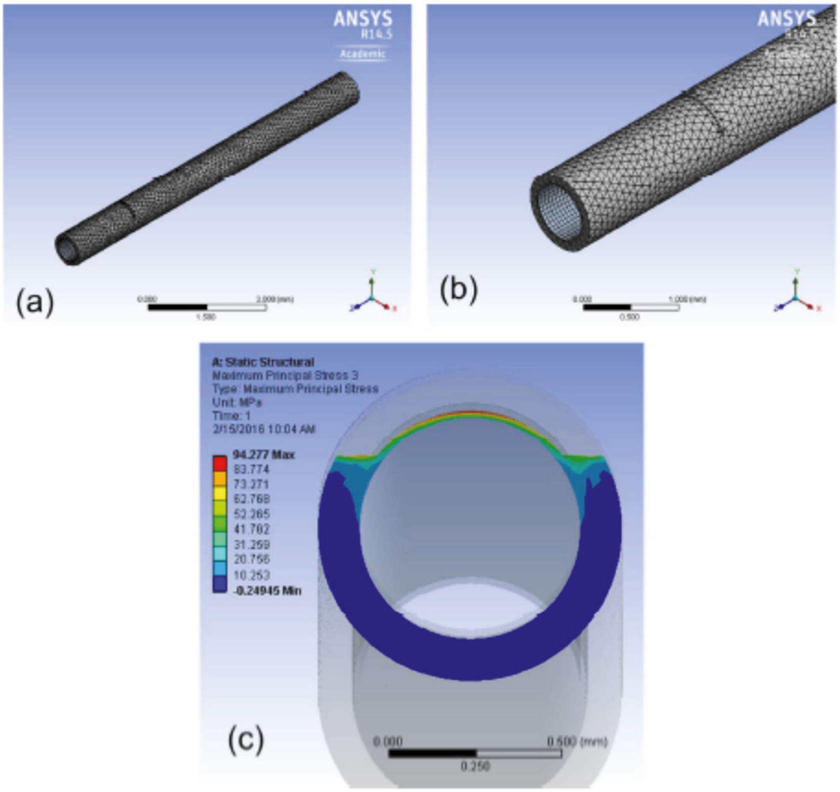

Figure 4: Finite element model of the leg of a locust containing a sharp notch and repaired with an endocuticle patch. Note the high stresses in the patch immediately below the cut surface.

This work demonstrates the existence of a sophisticated repair process by which an injury that significantly reduces structural integrity can be detected and repaired. This process is, we presume, orchestrated by living cells in the epithelial layer on the inside of the skeleton, but as yet little is known about the biology of this system.

4. Competing failure modes in thin walled tubes

Thin walled tubes under stress can fail in a number of different ways. The problem has been analysed by Wegst and Ashby (2007) for the case of bending in tubes made from orthotropic material, which is a common situation in plant stems such as bamboo. We extended this approach to consider mixed bending and axial loading as found in the exoskeletons of arthropods such as insects and crustaceans, and also in the tubular bones of humans and other vertebrates (Taylor and Dirks 2012). Figure 5 shows theoretical predictions which suggest that the optimal radius/thickness ratio r/t for the locust tibia in bending is 7.2. Tubes with larger values of r/t were predicted to fail by local elastic buckling, whilst tubes with smaller r/t were predicted to fail when the bending stress exceeded the strength of the material. Actual tibiae, tested when the adult insect was 14 days old, failed by buckling as predicted (Parle *et al* 2015). More recent results have shown that as the insect ages, r/t decreases as a result of thickening of the limb, passing through the optimal value, and the failure mode changes from buckling to fracture at the compressive strength of the cuticle, in accordance with our predictions. This suggests that the exoskeletons of arthropods have evolved to have the best possible strength to weight ratio, given the constraints of their particular method of making and growing their skeletons.

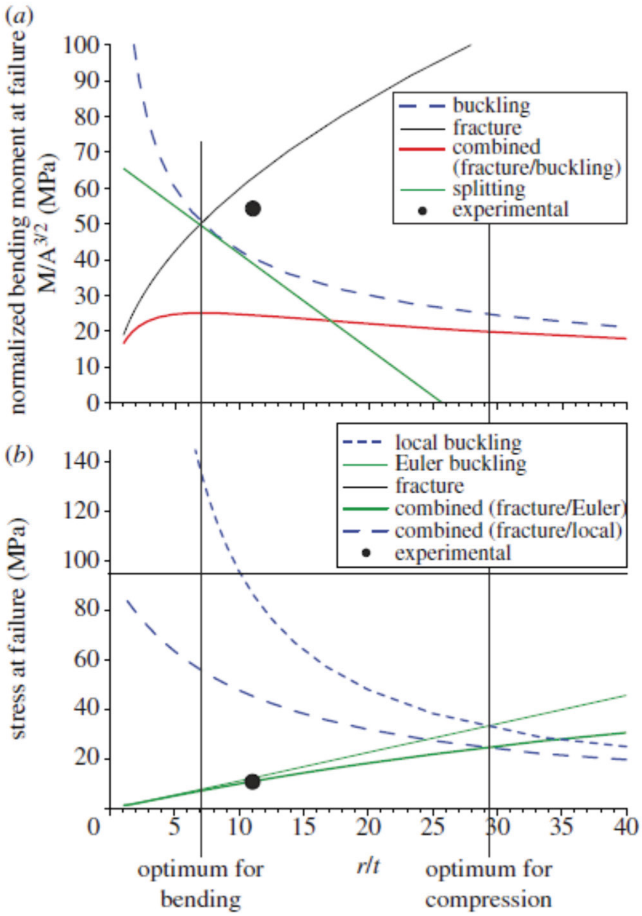

Fig.5. Theoretical predictions of optimum r/t ratios for insect cuticle in bending and in compression, with experimental results for the locust tibia at age 14 days.

5. Concluding remarks

Natural materials and structures, in common with their engineering equivalents, need to maintain structural integrity when subjected to applied forces. Nature works with a limited range of materials; almost all are composites in which a soft, polymeric phase is reinforced with a harder, stiffer phase in the form of fibres or other high aspect-ratio structures such as plates in nacre. These materials have, without exception, low toughness values, and are constantly under threat of failing by cracking, so fracture mechanics is very relevant if we wish to understand and learn from these materials. We find that they have developed some excellent strategies for maximizing toughness by introducing structure at the micro and nano scales. Furthermore, natural materials are often able to compensate for their poor resistance to damage development by using a continuous process of detection and repair, considerably increasing their effective strength and durability. At the level of the structural component, Nature comes under severe constraints to produce high strength/weight ratios in the face of competing failure modes. We find that, at least in some cases, evolution has worked in such a way as to provide solutions which are close to the optimum, given the practical constraints which apply.

In conclusion, the study of natural materials and structures is a fascinating topic, and one in which important discoveries can be made by applying well know concepts of fracture mechanics and structural integrity.

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