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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.