*Focussed on: Fracture and Structural Integrity related Issues*

# Fracture Mechanics: Inspirations from Nature

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**ABSTRACT.** In Nature there are many examples of materials performing structural functions. Nature requires materials which are stiff and strong to provide support against various forces, including self-weight, the dynamic forces involved in movement, and external loads such as wind or the actions of a predator. These materials and structures have evolved over millions of years; the science of Biomimetics seeks to understand Nature and, as a result, to find inspiration for the creation of better engineering solutions.
There has been relatively little fundamental research work in this area from a fracture mechanics point of view. Natural materials are quite brittle and, as a result, they have evolved several interesting strategies for preventing failure by crack propagation. Fatigue is also a major problem for many animals and plants. In this paper, several examples will be given of recent work in the Bioengineering Research Centre at Trinity College Dublin, investigating fracture and fatigue in such diverse materials as bamboo, the legs and wings of insects, and living cells.

**KEYWORDS.** Fracture; Toughness; Fatigue; Insect Cuticle; Bamboo; Osteoctyes.

## INTRODUCTION

In this paper (and accompanying lecture) I will be considering two material properties of vital importance in engineering: fracture toughness and fatigue strength. I will show the results of measurements of these two properties in various materials and discuss the significance of these results for the mechanical structures in which these materials are used. However, the materials and structures that I will consider are not from the world of engineering components; instead, they come from nature. If we look around us we see many natural, biological structures which are load-bearing and which are required to provide mechanical support and to ensure rigidity and long-term durability. These structures have not been designed in the way that engineering parts are designed, rather they have evolved over millions of years. In some ways these materials and structures are very different from their engineering equivalents, but nevertheless it can be interesting and perhaps useful to study them from an engineering perspective. Such studies shed light on aspects of the world in which we live, and may also lead to the development of improved engineering materials and components *via* a Biomimetics approach in which nature is seen as an inspiration and starting point for creative design activities.
Very little such work has been done to date from a fracture mechanics point of view. We have hardly any data on fracture toughness ($K_c$) and fatigue properties for natural materials, and little understanding about how these materials resist crack propagation and other failure mechanisms. In my research group we have been addressing this problem, starting some years ago with work on the fracture of bone, and moving in recent years to some of the other structural biological materials. In what follows I will describe three projects, spanning a large range of sizes from plants (which grow to heights

of several metres), to insects (of the order of millimetres) and finally to living cells in our bodies where the relevant scale falls below one micron.

## INSECT WINGS

Fig. 1 shows a crack-propagation test carried out on the wing of an insect – in this case a locust. We cut samples approximately 10mm x 10mm, introduced a notch of length approximately 1mm into one side, and applied axial tension. Further details can be found in a recent publication [1]. The wing consists of a sheet of material which is very thin (approximately 3μm) and which has veins of thicker material running through it at a spacing of approximately 1mm. We found that these veins improved $K_c$ by about 50% and that the spacing of veins was optimal: if they had been more closely spaced this would not have improved the stress to failure because the tensile strength of the material would be exceeded. Propagating cracks were seen to arrest at veins; on further loading the crack first blunted and then propagated *via* void formation on the far side of the vein, as shown in the figure.

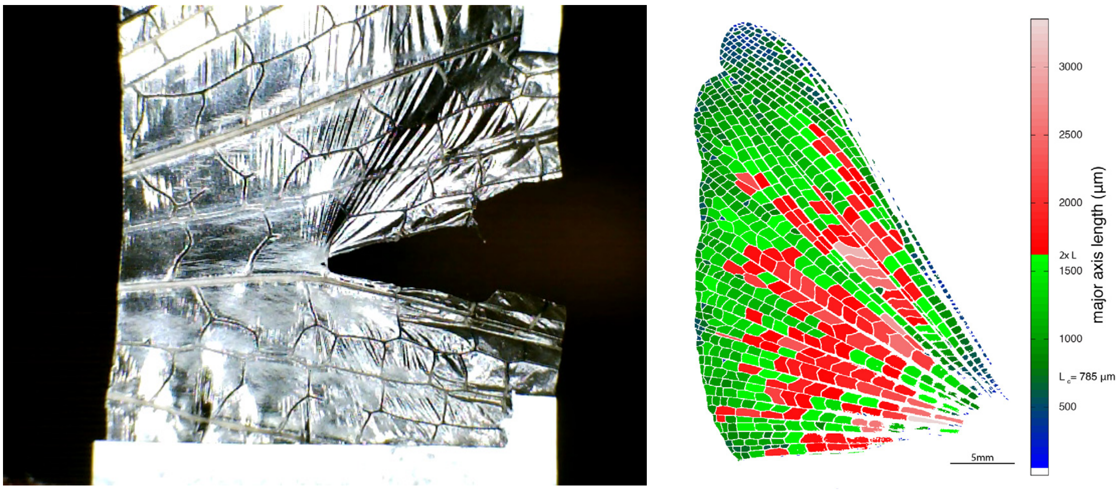


Figure 1: The image on the left shows a fracture toughness test on material from the wing of a locust, with a propagating crack arrested at a vein. The image on the right shows the entire wing; the different colours indicate the local spacings of the veins.

This experiment illustrates, in a very simple way, a concept which is applicable to all materials: the idea of a "critical distance". I have investigated in some detail the Theory of Critical Distances as applied to engineering materials (see for example [2]). The concept that any given material possesses a critical distance L which controls fracture and fatigue behaviour can be difficult to understand when applied to materials with complex microstructures: the insect wing presents a simple, two dimensional example of the essential idea: that materials contain microstructural features which inhibit crack propagation. When considering the effect of a crack or notch it is useful to compare the physical dimensions of the feature, and of the disturbance which it creates in the surrounding stress field, with the critical distance.

## BAMBOO

The stems of plants must be sufficiently rigid to allow upward growth and support of the leaves, and sufficiently strong and tough to resist mechanical forces, especially periodic wind loading. Bamboo is an important engineering material in its own right, extensively used in Asia and of great future interest because its fast growth makes it a renewable resource. However there have been relatively few publications on the mechanical properties of the bamboo stem, which is known as a "culm". Culms grow to heights of over ten metres, in the form of hollow tubes of almost constant thickness (see Fig. 2), with periodic nodes which carry thin branches to which the leaves are attached. In a recent project (the results of which are currently in review for publication) we assessed the mechanical effect of these nodes, showing that (despite previous assumptions to the contrary) they do not improve the stiffness or strength of the bamboo culm, and that (unlike the veins of the insect wing) they are too far apart to significantly improve toughness.

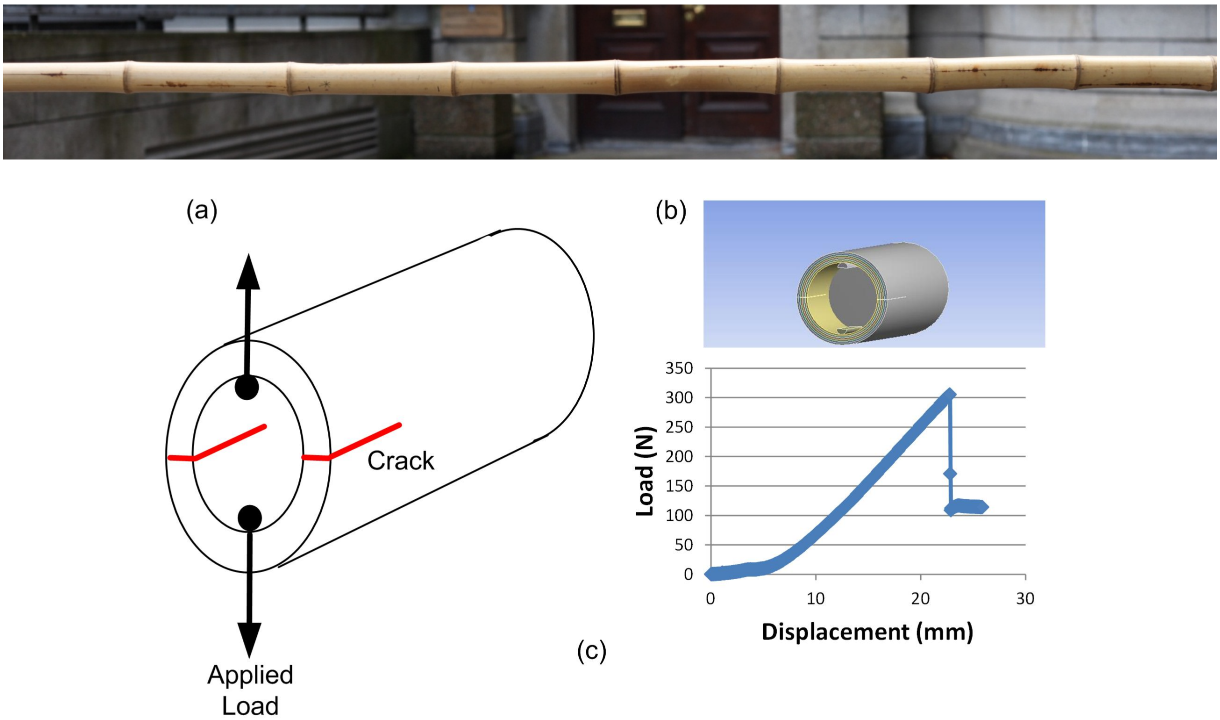


Figure 2: (Photograph): the bamboo culm consists of a hollow tube with periodic nodes. (a) We measured $K_c$ by propagating cracks along the tube axis by means of a pair of point loads. (b) We constructed a finite element model including the layered structure. (c) A typical load/displacement trace from a toughness test.

Measuring the fracture toughness of this material is quite challenging. It is highly anisotropic, and in fact it always fails by splitting (i.e. propagation of cracks in the longitudinal direction) whatever type of load is applied to it. Furthermore the tubular shape of the culm and the graded structure (consisting of layers of material varying in stiffness from outside to inside) make it impossible to use standard fracture toughness specimens. A number of previous studies have been published, reporting $K_c$ values which vary greatly, from as little as 0.18MPam$^{1/2}$ [3] to as much as 200MPam$^{1/2}$ [4]. In fact, the assessment of these various studies is a good lesson for the student of fracture mechanics, demonstrating how incorrect results can be obtained if one does not fully understand the underlying principles.
We measured $K_c$ by propagating cracks from notches, using a pair of point loads at one end of a tube sample (see Fig. 2a). Fracture toughness was estimated in two different ways: (i) using the maximum force at failure, along with a finite element model (Fig. 2b) to relate this force to the local stress intensity factor; (ii) using the fracture energy (the area under the force/displacement curve) divided by the area of new crack propagation to obtain the strain energy release rate. The two methods gave slightly different results (by about 30%) and consistently recorded a 55% increase when the crack tip was located at a node, suggesting a mechanical role for the nodes in limiting failure by splitting. However, subsequent calculations showed that the separation of the nodes was much too great: any crack which initiates would be able to propagate through the node on reaching it. Our conclusion is that these nodes fulfill a biological function (as branch points) but do not confer any mechanical benefit on the plant.

## FATIGUE OF NATURAL MATERIALS

Cyclic loading is very common in nature, and many biological materials fail by fatigue, but as yet we know very little about their fatigue characteristics. One exception is bone, which has been studied quite extensively [5]: fatigue cracks initiate in bone as a result of normal daily activities but usually do not propagate to failure thanks to bone's self-healing ability. Excessive loading (e.g. in professional athletes) or poor-quality bone (e.g. due to osteoporosis) gives rise to fatigue failures which are referred to by doctors as "stress fractures". Recently we have been carrying out tests to measure, for the first time, fatigue behaviour in three other natural materials: insect cuticle; bamboo and cells.

Fig. 3 shows fatigue data on the legs and wings of insects, from a recent publication [6]. These body parts are made from essentially the same material – known as "cuticle" – but the cuticle found in the legs contains more fibres of chitin and is significantly anisotropic. This is reflected in the smaller fatigue range for leg material, with an endurance limit at one million cycles around 70% of the failure stress, in contrast to the wing material which shows fatigue at less than 50% of its tensile strength. Legs (which are essentially hollow, thin-walled tubes) were tested in cyclic cantilever bending and displayed two different failure modes: traditional cracking on the tensile side and progressive buckling on the compression side, suggesting that the evolution of these body parts has generated an optimal structure, equally resistant to failure in compression and tension.

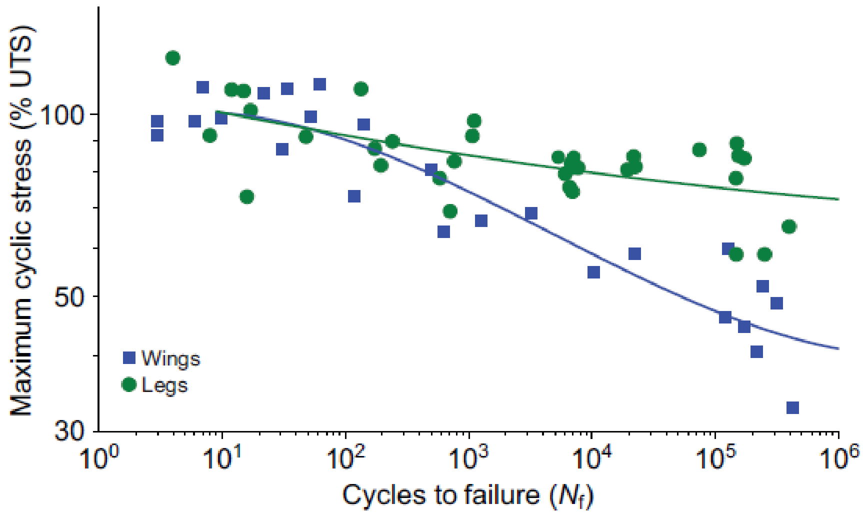


Figure 3: Stress-life fatigue data for insect legs and wings.

Fig. 4 shows data (as yet unpublished) for bamboo. Surprisingly, we could find no fatigue data for this material in the published literature, despite its widespread use. These data were generated by cutting tube samples from the culm and loading them in compression across the diameter, thus generating fatigue failure by longitudinal splitting. A large fatigue range exists, which should be taken into account when this material is employed for structural purposes.

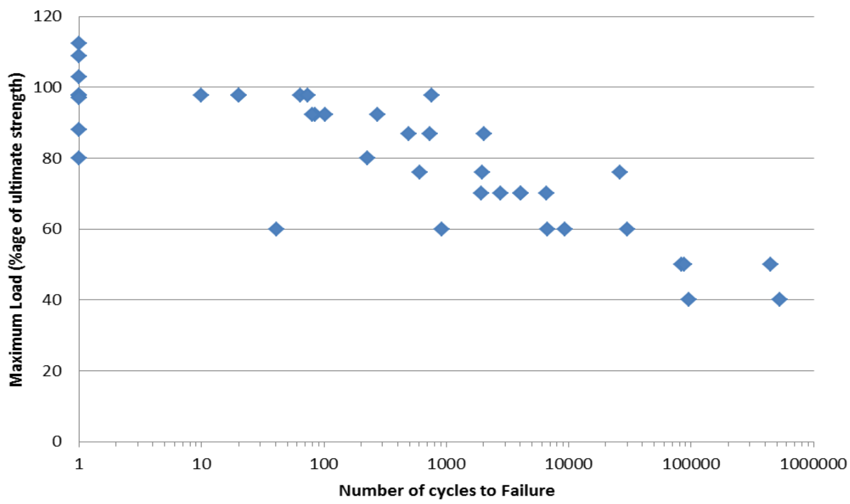


Figure 4: Stress-life data for bamboo culm samples

My final example of fatigue in natural materials concerns living cells. Our bodies, and those of animals and plants, contain different types of cells, which perform specific functions. Many cells experience cyclic loading, so the question arises as to whether they ever fail by fatigue. This is a difficult question to answer by experimental means: cells are small (typically 10-100μm in diameter) and very soft and flexible, consisting of an outer membrane of lipid molecules supported by a

cytoskeleton consisting of relatively stiff protein molecules which line the membrane and also pass across the cell body, conferring some overall rigidity and allowing the cell to move and change shape.
Though there have been a number of studies to measure the elastic stiffness and viscoelastic properties of cells, there are only a very few reports of monotonic tests to failure, and no data on fatigue failure for any type of cell. We devised a test which makes use of the fact that a certain type of cell – known as an osteocyte – lives inside our bones. These cells are connected to each other via long, thin extensions of the cell body known as cellular processes (see Fig. 5).

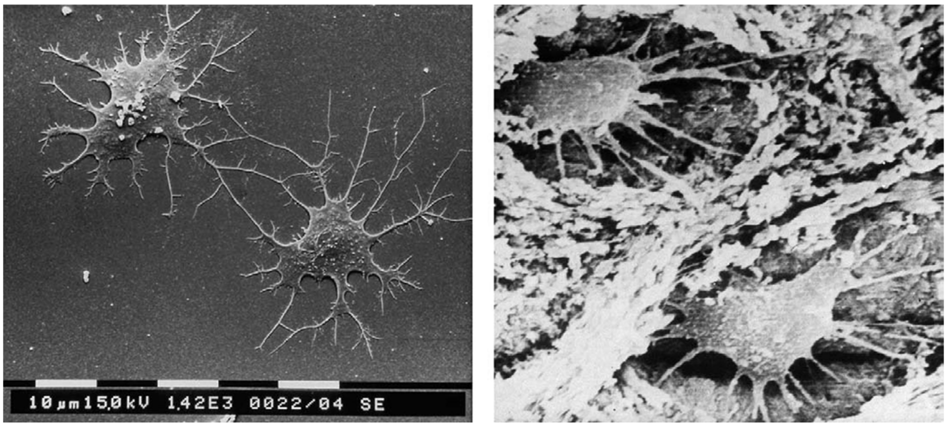


Figure 5: Osteocytes are linked together in a network *via* numerous cellular processes: these images show examples of cells with and without the surrounding bone matrix [7].

We noticed that, where a bone contains cracks, these cellular processes can be seen passing across the open crack. Therefore, by applying cyclic loading to the bone, causing these cracks to open and close, we could conduct fatigue tests on individual cellular processes. Our initial results were published showing the number of cycles to failure as a function of cyclic crack opening [8]; in more recent work (shortly to be published in the *Journal of the Mechanical Behavior of Biomedical Materials*) we used finite element modelling to estimate the cyclic strain and therefore generate the first ever strain-life curve for material taken from a living cell (see Fig. 6).

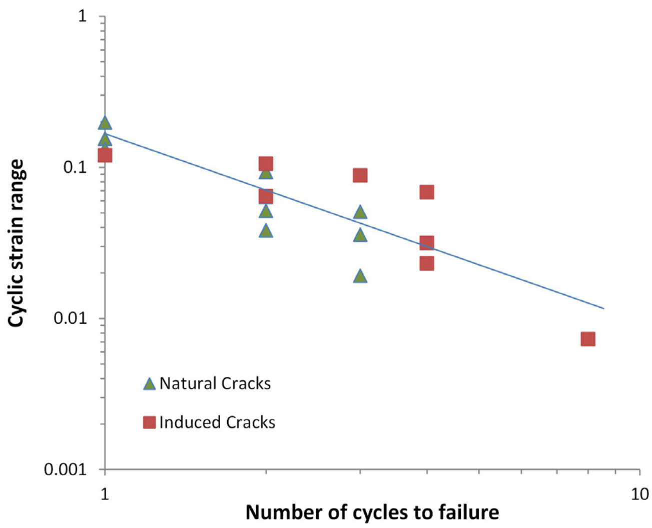


Figure 6: Strain-life data for osteocyte cellular processes.

This work has some significant limitations: in order to observe failure of these cellular processes (which are only 200nm in diameter) we had to conduct the tests inside a scanning electron microscope using an *in situ* loading stage. Limits on resolution meant that we were only able to measure relatively large strains and therefore small numbers of cycles to failure, up to 10. Interestingly the results are quite similar to fatigue of metallic materials in the very low cycle regime.

These findings are of importance because we believe that the fatigue failure of these cellular processes, at the point where they span an open crack in the bone matrix, could be a crucial step in the complex system by which fatigue cracks in bone are repaired, ensuring the continued integrity of the skeleton.

## CONCLUDING REMARKS

There are perhaps two different reasons for engaging in the type of research described above. The first is simple curiosity. It has been fascinating to discover how Nature solves the same problems of structural integrity as those faced by engineering designers and materials scientists. The second reason is that in this way, inspiration may be provided to create new, biomimetic materials and structures. Nature's materials are, in many ways, not as good as modern engineering materials. They tend to have lower fracture toughness values and to suffer from fatigue at least as much. But Nature has evolved some clever strategies to overcome these limitations – strategies such as self-repair and the use of functionally graded materials – so that keeping an eye on Nature may help us to create new, better solutions for engineering applications.

## ACKNOWLEDGEMENTS

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