Crack Paths in the Fatigue and Fracture of Bone

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ABSTRACT. *Bone is a highly anisotropic material, having an easy crack growth direction which is approximately parallel to the bone's longitudinal axis. This creates anisotropy in its fracture toughness and strongly affects the orientation of naturally occurring cracks* in vivo *and the initial growth direction of cracks extending from notches. In this paper we show three examples to illustrate how fatigue and fracture behaviour is affected by this anisotropy and how a knowledge of the crack path can help in making fracture mechanics predictions of fatigue and fracture behaviour under different external loading conditions.*

INTRODUCTION

Bone, in common with most of the materials in nature which have load-bearing functions, is essentially a fibrous material, being made up of long-chain molecules of the natural polymer collagen and elongated plate-like crystals of the ceramic material hydroxyapatite. These two materials are arranged in layers in a manner similar to that found in fibre composite laminates. The fibre orientations are varied in the different layers, somewhat reducing the anisotropy but nevertheless maintaining a strong preference for the longitudinal direction of the bone. These laminae also bend around to form tubular structures known as osteons, of diameter approximately 200μm, each containing a central blood vessel. The morphology of this microstructure is different in some animals, but in all cases the resulting bone has a strong degree of anisotropy: measured values of tensile strength and fracture toughness for loading in the transverse direction are typically one third to one half those measured for longitudinal loading.

Bone has a fairly low toughness and fatigue crack resistance, so cracks form quite easily as a result of normal daily activities. Normally these cracks reach lengths no greater than a few hundred microns before they are arrested by microstructural features, especially osteon boundaries, as shown in fig.1, and are subsequently repaired by groups of cells which periodically replace old bone with new bone. In some circumstances these cracks may grow faster than they can be repaired, giving rise to fatigue failures, clinically known as "stress fractures", which are often experienced by athletes, dancers and military personnel due to excessive exercise, and to fragility fractures in older people whose bones are more brittle.

Another failure problem in bone is the effect of stress concentration features such as drill holes left by surgery and defects remaining after complex fractures. Fatigue or brittle fracture may be initiated from these locations in a classic example of notch weakening.

The present paper describes three pieces of work which we conducted to examine crack paths in bone and to use this understanding of crack orientation to make quantitative predictions of fatigue and fracture behaviour.

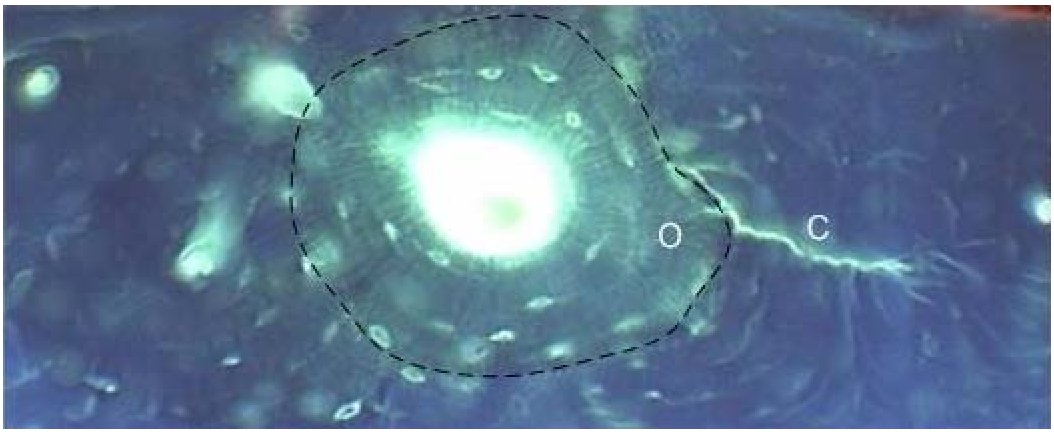

Figure 1: Image taken using fluorescence microscopy, of a transverse section through a bone, showing an osteon (O), diameter approximately 200μm, and a crack (C) which has arrested at the osteon boundary. From O'Brien et al [1].

FATIGUE OF BONE IN TENSION, COMPRESSION AND TORSION

We conducted tests to measure the fatigue strength of bone in compression and torsion, using both whole bones and regular cylindrical test specimens. We also analysed a large amount of data from the literature on fatigue testing of bone in tension and compression. Comparison of data from different sources is complicated by a number of influential factors, such as specimen size, loading frequency and temperature but a rational comparison is possible if all factors are taken into account, as described elsewhere [2]. We found that bone's high-cycle fatigue strength was greatest in compression. It is considerably lower in torsion, the ratio of fatigue strengths in compression to torsion being 2.2. In tension it is just slightly weaker, the ratio of compression to tension being 1.16. In cyclic torsion, cracks tended to form and grow in a direction approximately parallel to the longitudinal axis of the specimen (which coincided with that of the bone) as shown in fig.2.

We hypothesised that this behaviour could be predicted using fracture mechanics, based on the idea that fatigue failure occurred by the growth of pre-existing small cracks. We analysed microscopy data from our own work and that reported in the literature, to determine the typical size, shape and orientation of these *in-vivo* microcracks [3]. We found that, unlike metals and many other materials, cracks do not form preferentially on the surface: the majority of cracks are internal. A typical crack is elliptical in shape, having a minor axis of 100μm, lying in the transverse direction and a major axis of 450μm lying at a slight angle to the longitudinal direction, as shown in fig.2. The misorientation angle θ is typically 10-20^{o}C, which is similar to the misorientation of the osteon axis, but may take somewhat higher or lower values.

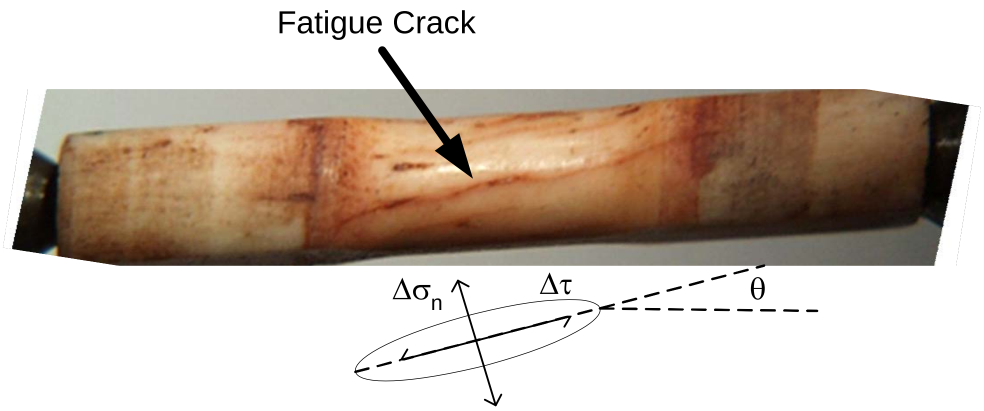

Figure 2: Photograph showing typical crack path during torsion fatigue testing; some portions of the crack are parallel to the specimen axis whilst some are at a slight angle. Also shown is a schematic of the shape and orientation of a typical *in-vivo* microcrack, subjected to normal and shear stresses.

We carried out a fracture mechanics analysis as follows: the relevant crack loading modes are an opening mode (Mode I), caused by a cyclic tensile stress $\Delta\sigma_n$ and a sliding mode (Mode II or III, depending on crack front position) caused by a shear stress $\Delta\tau$ in the plane of the crack (see fig.2). We defined an effective stress $\Delta\sigma_e$ as follows:

$$\Delta\sigma_e = (\Delta\sigma_n^2 + \Delta\tau^2)^{1/2} \tag{1}$$

In a specimen subjected to applied axial tension, both $\Delta\sigma_n$ and $\Delta\tau$ are positive, whilst in axial compression $\Delta\sigma_n$ is negative and thus is assumed to have no effect. This leads to a higher fatigue strength in compression, by a ratio which depends on the angle θ. Some simple mathematics shows that the experimentally determined ratio of 1.16 is satisfied by $\theta = 30.5^{o}$. This is physically reasonable because in general there will be many microcracks in the specimen, lying at a range of angles, and failure will occur from the one lying at the greatest angle, for which 30^{o} is a plausible value.

For a specimen subjected to axial torsion, on the other hand, one can show using the same equation that the most dangerous value of θ will be zero. Assuming failure at the same effective stress as defined in equation (1), this leads to a prediction of 2.28 for the ratio between compression and torsion fatigue strengths, which is a very good prediction of the experimental value of 2.2.

This approach gives a more accurate prediction than the use of Von Mises or Tresca criteria, which in any case would be less appropriate from a mechanistic point of view. Since we aimed only to predict the ratios between the three fatigue strengths, it was not necessary to specify exact values for the fatigue thresholds of these cracks. This is fortunate because exact values are not known, and these cracks are certainly short cracks and so will have lower threshold values than long cracks. This analysis also emphasises the importance of the crack orientation angle. Cracks seem to run parallel to osteons, so why are the osteons not oriented exactly parallel to the bone's axis? This question has not been satisfactorily answered but it may be because the principal stress axis *in vivo* is not exactly parallel either, and varies depending on the type of activity, so the osteon orientation may represent a compromise solution.

CRACK PATHS IN NOTCH-INDUCED FRACTURE

The examination of broken bones shows that, macroscopically, cracks tend to orient themselves so as to grow perpendicular to the maximum principal stress, as one might expect in a brittle material. Thus, for example, fractures caused by torsion give rise to spiral cracking in which the crack follows a helical path around the bone tube. We were interested in finding out the exact crack path for the early stages of brittle fracture, to enable us to use the Theory of Critical Distances, of which more will be said below. We hypothesised that the initial crack path would lie not perpendicular to the principal stress but rather parallel to the easy direction of crack growth, i.e. approximately longitudinal to the bone's axis.

We tested this hypothesis by preparing cracks with double notches. This technique, which has been used very effectively by Ritchie and co-workers [4], involves machining two identical notches into a specimen – in our case a four-point-bend specimen – and loading it to failure. Failure occurs from one notch, leaving the other frozen in a state just prior to failure. Often, examination of this notch reveals a small crack which has initiated but not propagated very far. This is a very useful technique for studying fracture development in brittle materials. As fig.3 shows, we found that the initial crack path was always close to the bone's longitudinal axis, whatever the orientation of the specimen and loading direction. When the crack became longer and had much more energy it was able to grow perpendicular to the principal stress, though even then there was often much branching and secondary growth along the longitudinal direction.

Incidentally, one of the cracks shown in fig.3 displays the phenomenon of crack-face bridging by unbroken ligaments, which has been identified as an important toughening mechanism in bone [4].

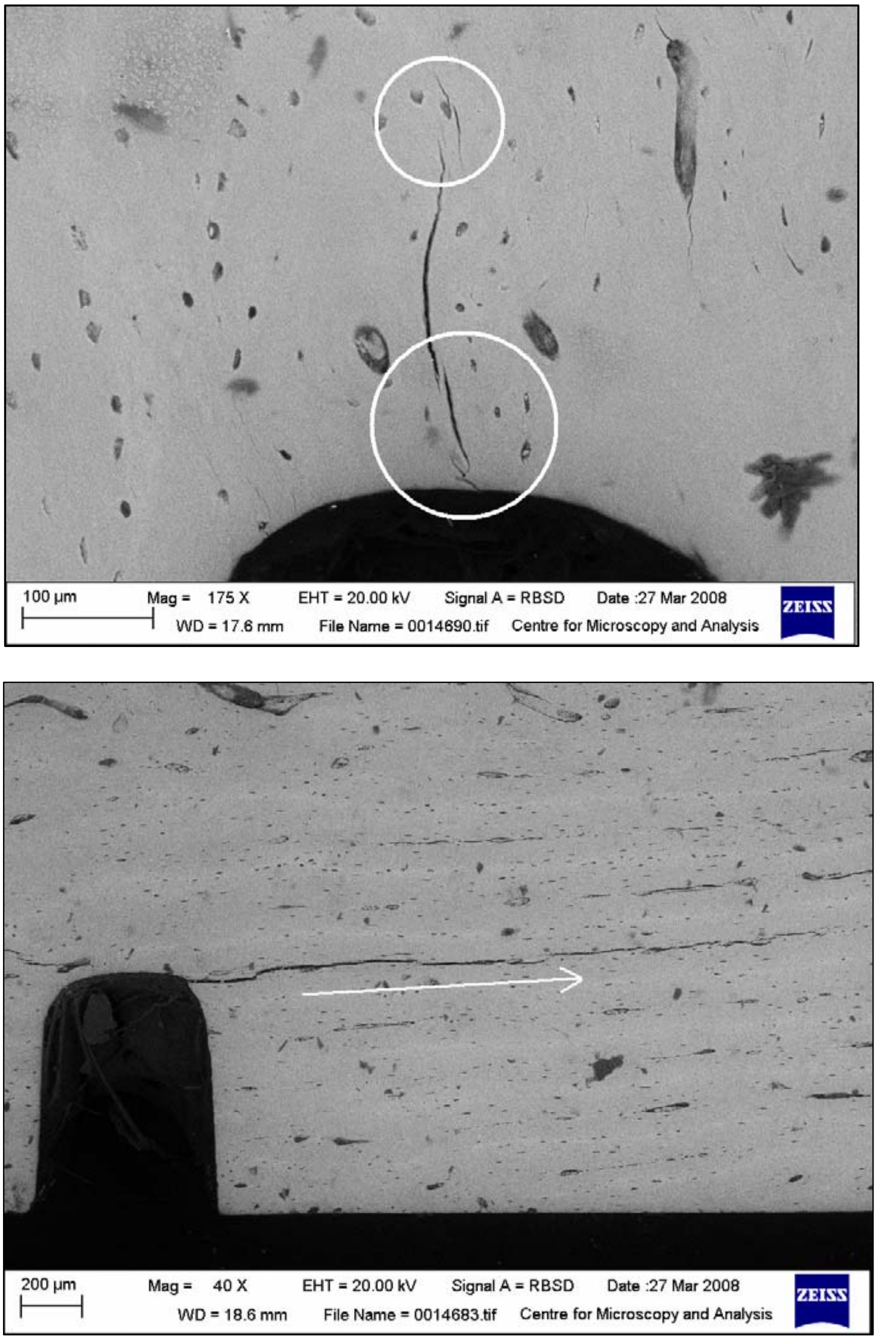

Figure 3: Typical crack paths for early crack growth from notches: SEM photographs taken from double-notch specimens. In the top photograph the bone's longitudinal axis is vertical, parallel to the notch direction. Note regions of crack bridging (circled). In the bottom photo the bone's longitudinal axis is horizontal, perpendicular to the notch direction: traces of osteons can be seen running almost horizontally. In both specimens the initial crack path is close to the longitudinal direction.

INDENTATION FRACTURE

We carried out tests to measure the fracture behaviour of bone under indentation loading with a sharp metal blade, as part of a study into bone cutting and instrument sharpness. Cubes of bone of side length 8mm were indented on the centre of one face. We discovered that, as in the case of the notched specimens above, the initial crack paths were always parallel to the bone's longitudinal axis, leading to very different failure modes depending on the relative orientation of the bone and the blade. If the direction of blade motion was the same as the longitudinal direction of the bone, then samples split easily as a result of crack propagation in this direction, and the force needed was relatively low. But when the direction of blade motion was perpendicular to the longitudinal direction of the bone, the crack path was still the longitudinal one. Cracks grew perpendicular to the blade, parallel to the specimen surface and material was removed from the surface by periodic spalling. The force/distance graph for this test had a series of maxima and minima corresponding to each spalling event. Figure 4 shows typical specimens after staining to reveal the cracks.

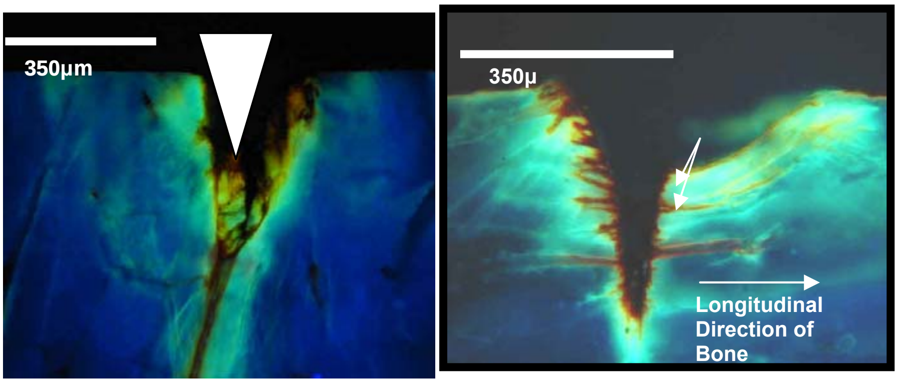

Figure 4: Specimens fractured by indentation, stained and viewed by fluorescence microscopy. On the left, the blade (shown schematically as a white wedge) indented the specimen parallel to the bone's longitudinal axis, creating a single crack which propagated in a downwards direction. On the right, the blade direction is the same but the specimen was rotated through 180^{o} making the longitudinal axis horizontal. Multiple small cracks formed and propagated horizontally (the white arrows show two examples), causing spalling which has removed some material on the right hand side of the indentation.

Knowing the initial crack growth direction enabled us to carry out an analysis using an approach known as the Theory of Critical Distances (TCD). The TCD is a method which is frequently used to predict fatigue and brittle fracture from notches and other stress concentrators [5], using information from the stress field in the immediate vicinity of the stress concentration feature. The theory takes various different forms but the easiest ones to implement in conjunction with finite element analysis are those which use the stress at a point, or averaged along a line. This line, known as the focus path, starts at the maximum stress point (at which cracking is assumed to initiate) and is drawn in the direction of crack propagation. Previous work on bones containing cracks and notches had shown that the critical distance L, which is essentially the size of the zone in which failure processes occur, had a value of 0.3-0.4mm in cortical bone [6]. This is the same order of magnitude as the size and spacing of osteons, suggesting that these play a strong role in determining the material's fracture toughness. We used the TCD, taking the focus path to be always the longitudinal direction, and applying a multiaxial criterion to the stress tensor at the critical distance, which for the point stress method is L/2. We were able to predict the indentation force required to fracture the bone for both orientations of the indenter relative to the bone (see fig.5), as well as the effect of the indenter geometry, i.e. the sharpness (root radius) of the blade and the wedge angle.

There have been only a limited number of studies of indentation and cutting in bone, despite its great importance in surgical procedures. To our knowledge this is the first time that the TCD has been used to predict indentation fracture in any material, though it has been used previously to predict contact/fretting fatigue [7].

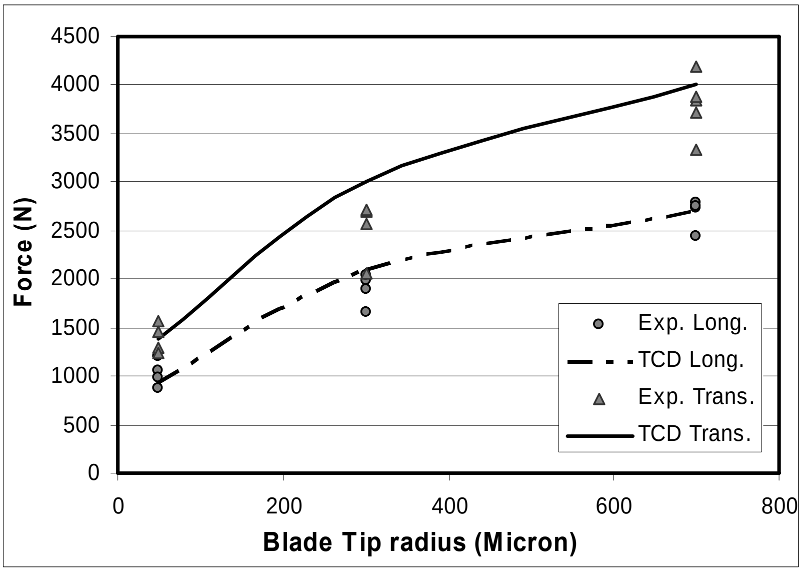

Figure 5: Experimental data (points) and predictions (lines) for the indentation fracture force, as a function of blade tip radius and orientation. Long.= blade oriented in the bone's longitudinal direction; Trans.= blade oriented perpendicular to the bone's longitudinal direction.

DISCUSSION

The work described above is rather unusual in the field of crack path studies. Engineering materials are usually isotropic and therefore the paths which cracks take are determined by the stress fields which arise as a result of loading and geometry. Multiaxial criteria are used to first predict crack growth directions and then assess fracture resistance once these directions are established. In the present case, however, the crack path is, to a large extent, predetermined by the anisotropic structure of the material, at least for small cracks in the crucial early stages of growth. This simplifies the problem of predicting the crack path, but complicates the fracture mechanics analysis: in isotropic materials the crack will generally orient itself normal to the maximum principal stress, which then usually becomes the dominant stress, but in bone the growing crack may experience a complex mixed-mode loading situation.

Other natural materials such as wood are also anisotropic, in fact all biological materials which have load-bearing functions are anisotropic and most are made up of fibrous structures carefully oriented along major loading directions. Wood, in fact, is even more anisotropic than bone and very commonly splits along its grain direction. It differs significantly from bone in being much weaker in compression than tension, by about a factor of two, so compression failure by fibre buckling is also a common fracture mode. Bamboo has a tubular form which is very prone to longitudinal splitting under bending loads; it protects itself by building in periodic crack-arresters: diaphragms which divide the tube into chambers.

The work described here has demonstrated that bone, though it has some unusual characteristics, is nevertheless amenable to analysis using fracture mechanics. More work is needed before we have a good understanding of the fracture properties of this material, of how it achieves its toughness and fatigue resistance through structure at various different hierarchical scales, and of how it continuously repairs itself to maintain structural integrity.

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