

MECHANICAL FAILURE ON THE MICROSTRUCTURAL  
LEVEL IN HAVERSIAN BONE\*

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INTRODUCTION

The object of this paper is to present several situations of failure on the microstructural level in bone which, while probably not occurring under ordinary physiological conditions, add to our understanding of the mechanical consequences due to the structural heterogeneity of bone. Specifically, this paper shall concern itself with fractures at three basic levels of microstructure; fractures around osteons through the cement lines, fractures through single osteons and micro-samples containing several osteons and fractures through the interlamellar regions between the collagen rich lamellae of single osteons.

INTEROSTEONIC FRACTURES -- CEMENT LINES

Cement lines are generally believed to be regions of high mineral and low collagen density [1]. As such, their ability to absorb energy without failure can be suspected to be less than that of the surrounding bone tissue. Furthermore, the general structure discontinuity which they present should also add to their general weakness. Piekarski's observations [2] suggest that slowly propagated fractures have a tendency to circumscribe the osteons although it is difficult to tell whether they propagate through the cement lines themselves.

This general tendency for fracture propagation was in fact successfully exploited in isolating single osteons of a wide range of lengths [3]. It appears that fractures in osteons with aspect ratios up to several times that of unity can actually be propagated through cement lines. Figure 1 shows a thin transverse cross-section subjected to bending by hand; fracture propagation clearly favors the osteon boundaries. A closer look at fracture propagation through cement lines is possible with Figure 2. The fracture between the osteon and the adjacent interstitial bone was produced by applying pressure with the tip of a scalpel blade over a small region of the observed fracture site (oblique arrow). Note the reasonably corresponding pair of fractured surfaces and their eventual convergence at the intact portion of the cement line (vertical arrow). Note also the relatively smooth wavelike contour displayed by portions of the fracture surfaces as well as by portions of the intact cement line (horizontal arrow). These observations point to the fact that, under the proper conditions, fractures can propagate through cement lines.

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## OSTEONIC FRACTURES

Fracture studies of the single osteon are free of the effects of cement lines and thus enhance the possibility of understanding failure mechanisms influenced by internal microstructure. But just as fracture propagation must be allowed to progress in such a manner which tends to promote its course along the weak interfaces between osteons, so too, must this general condition be met in studies on the osteon in order that minimum energy dissipation be the controlling factor. Thus, the fracture will proceed along the paths of least resistance which reflect the nature of osteon microstructure. This involves the loading mode with respect to the geometry of the microstructure as well as the rate of fracture propagation. Failure to meet this criteria results in fractures which tend to reflect the behavior of structurally homogeneous materials. The microfractures created in single osteons subjected to compressive load directed along the osteon axis [4] are not indicative of any microstructural features of the osteon, but rather are representative of material failures occurring along the planes of maximum shear stress, which for a homogeneous isotropic material would be inclined at  $45^\circ$  with respect to the loading direction, but which for the single osteon occur at angles near  $30-35^\circ$  with respect to its axis.

Another example of bone fracture not influenced by the microstructure can be found in an osteon fractured by cyclic (10 hertz) torsional stress overload, Figure 3. The fracture site presents a spiral, well defined surface indicative of a brittle, structurally homogeneous material; no microstructural effects were noticed. A closer look with scanning electron microscopy reveals an additional fracture plane; this is a consequence of the cycling mode which alternates the plane of maximum tensile stress from the  $45^\circ$  plane (for a homogeneous isotropic material) to the  $135^\circ$  plane upon reversal of twist direction. Although failure must have initiated at one plane, the other plane apparently was also made to reveal the history of destructive tensile stresses, see Figure 4.

When subjected to unidirectional torsional overload microsamples containing several osteons such as shown in Figure 5, displayed only one fracture plane inclined at less than  $45^\circ$  with the general osteon axis. The spiral fracture plane was not equally visible in all samples. The inclination of these fracture planes with respect to general osteon axis are comparable to those obtained with respect to the bone axis for whole dog tibias and femurs subjected to unidirectional torsional loading [5]. Samples containing several osteons subjected to fatigue by torsional cycling exhibited general fracture planes of less than  $45^\circ$  (with respect to the general osteon axis), which were not well-defined, but rather highly irregular. Microstructural consequences of fatigue-induced failures are still under study.

## INTRAOSTEONIC FRACTURES

Intraosteonic fractures have been observed in osteons subjected to compressive forces applied either in the direction of the osteon axis [4] or perpendicular to it [6]. In the former case, previously referred to, the microfractures created do not reflect the osteon's microstructural features. This is most likely due to the fact that the mode of loading does not favor preferential energy dissipation through the microstructural weakness of the osteon. However, loading an osteon perpendicular to its axis results in tensile radial and shear stresses over certain of its regions, which results in fractures indicative of its microstructural feature. According

to the authors [4], fractures are propagated either circumferentially through lamellae or radially through them, depending on the type of collagen fiber arrangement of the osteon tested.

Subjecting decalcified single osteons with aspect ratios of one or less to compressional loading in the direction of the osteon axis results in a completely different failure mechanism from that obtained for undecalcified osteons; the collagen-rich lamellae detach themselves from each other at their interfaces as seen in Figure 6. This is accomplished not with a single loading, but with repeated loadings applied with finger pressure to the wet osteon sample sandwiched between two glass slides. No microfissures are produced in the elastic wet collagen sample as occurs with the undecalcified osteons; rather, the damaging stresses are transmitted to the weak interlamellar region which once decalcified are believed to consist of a relatively low density of collagen structures as well as of presently unidentified ground substance components [7].

With each compressive loading the osteon contracts along its axis and expands in the direction perpendicular to it. The collagen lamellae themselves remain undisturbed, but the interlamellar constituents eventually fail and a clean separation between collagen lamellae results. That radial tensile forces are at least partially responsible for this failure mode can be appreciated from evidence of radially disposed broken collagen fibers which, prior to the sustained damage, bridged across consecutive collagen-rich lamellae [8].

The study of failure mechanism in microsamples of bone may have little or no clinical significance (except, perhaps, in the case of march fractures), but it can be valuable in developing an understanding for the interrelationship between microstructure and mechanical behavior in bone.

## ACKNOWLEDGEMENTS

This research has been supported in part by the National Institutes of Health - National Institute of Dental Research, Research Grant Number ST1-DE-117-13, and in part by the Orthopaedic Department Research Fund of Jefferson Medical College of Thomas Jefferson University.

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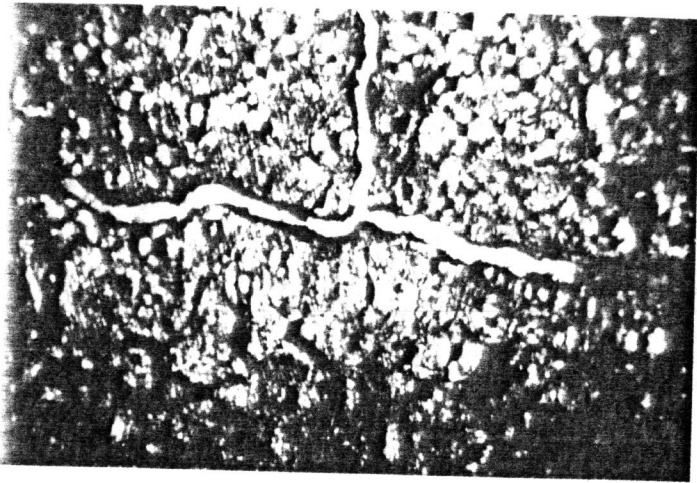


Figure 1 Thin cross-section of human cortical bone broken by bending by hand. Note the tendency of fractures to circumvent osteons. Mag. 30X.

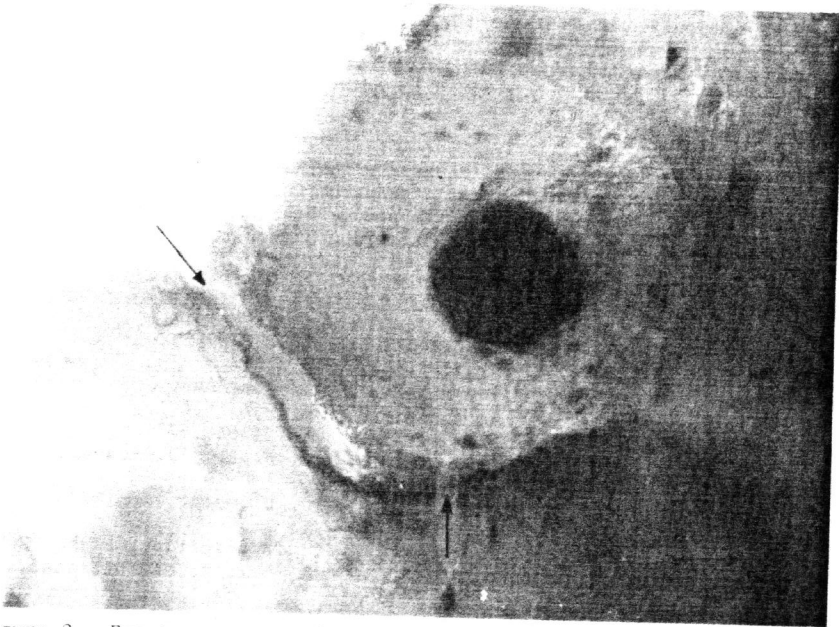


Figure 2 Fracture propagation through a portion of the cement line bordering between an osteon and interstitial bone belonging to a thin transverse cross section of human cortical bone. Mag. 250X.

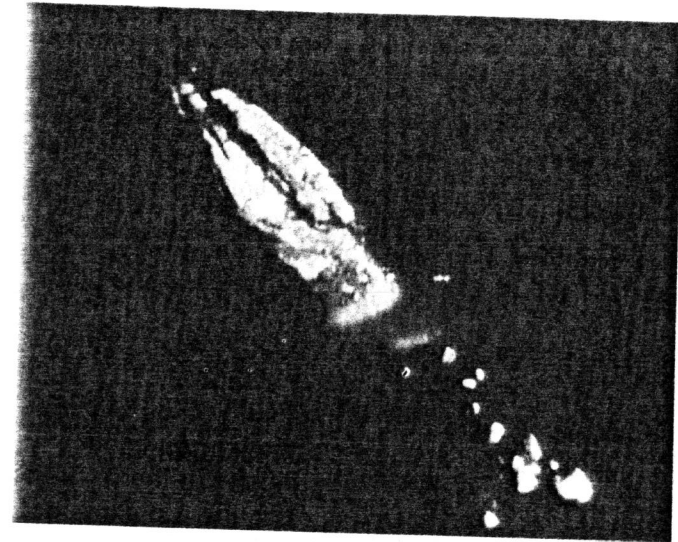


Figure 3 Portion of a single human osteon broken by cyclic torsional stress overload at a frequency of 10 hertz. Note the exposed Haversian canal as well as the spiral nature of the fracture surface inclined at about 30° with the osteon axis. Mag. 75X

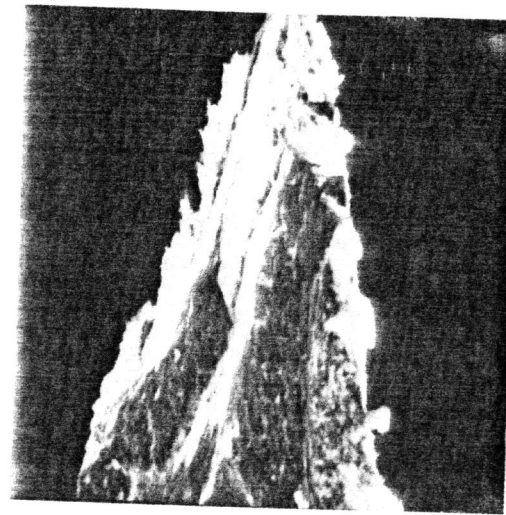


Figure 4 Osteon sample of Figure 3 observed with scanning electron microscopy. Note the two fracture planes - inclined at about 30° with the osteon axis - representative of cyclic rather than unidirectional stress overload. Mag. 200X

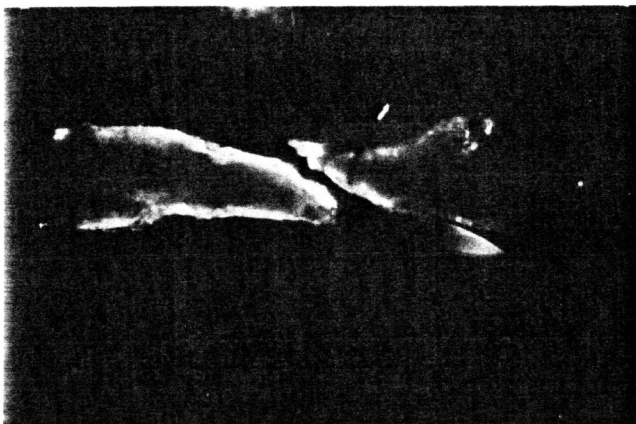


Figure 5 Microsample of human cortical bone containing several osteons, broken by unidirectional stress overload. The fracture planes are inclined at less than  $45^\circ$  with the osteon axis. Mag. 25X.

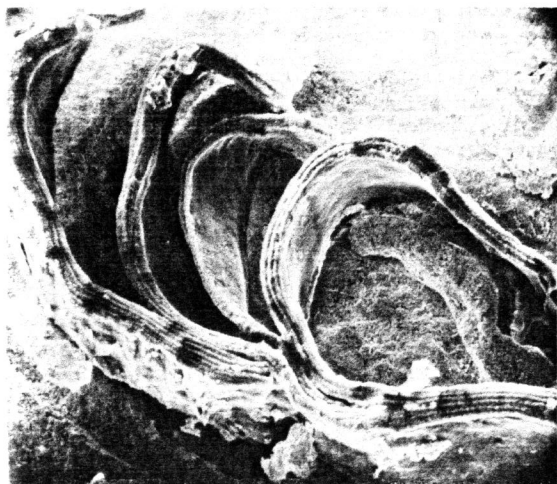


Figure 6 EDTA decalcified human osteon sample subjected to repeated fingertip compression between two glass slides until some collagen-rich lamellae were forced to separate from each other at their interface. Mag. 200X.