3.032 Mechanical Behavior of Materials

Fall 2007

Fatigue fracture/failure case study: Human bone

Image source: Naza, Krulick, Kinney and Ritchie. Biomaterials 26 (2005) 217-226.

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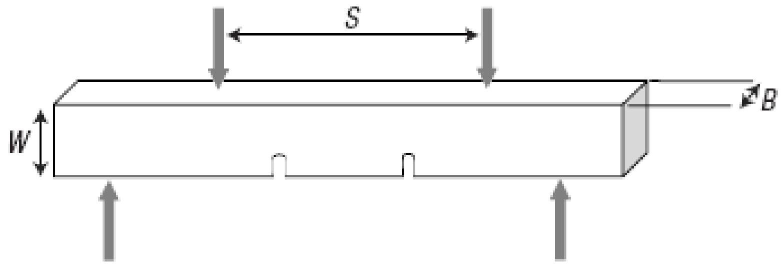
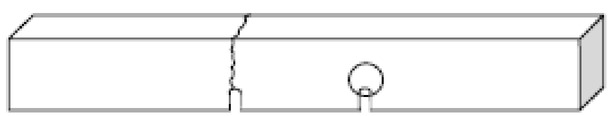
How to test bone fracture: Double-cantilevered beam



Before fracture



After fracture

Courtesy of R. O. Ritchie. Used with permission.

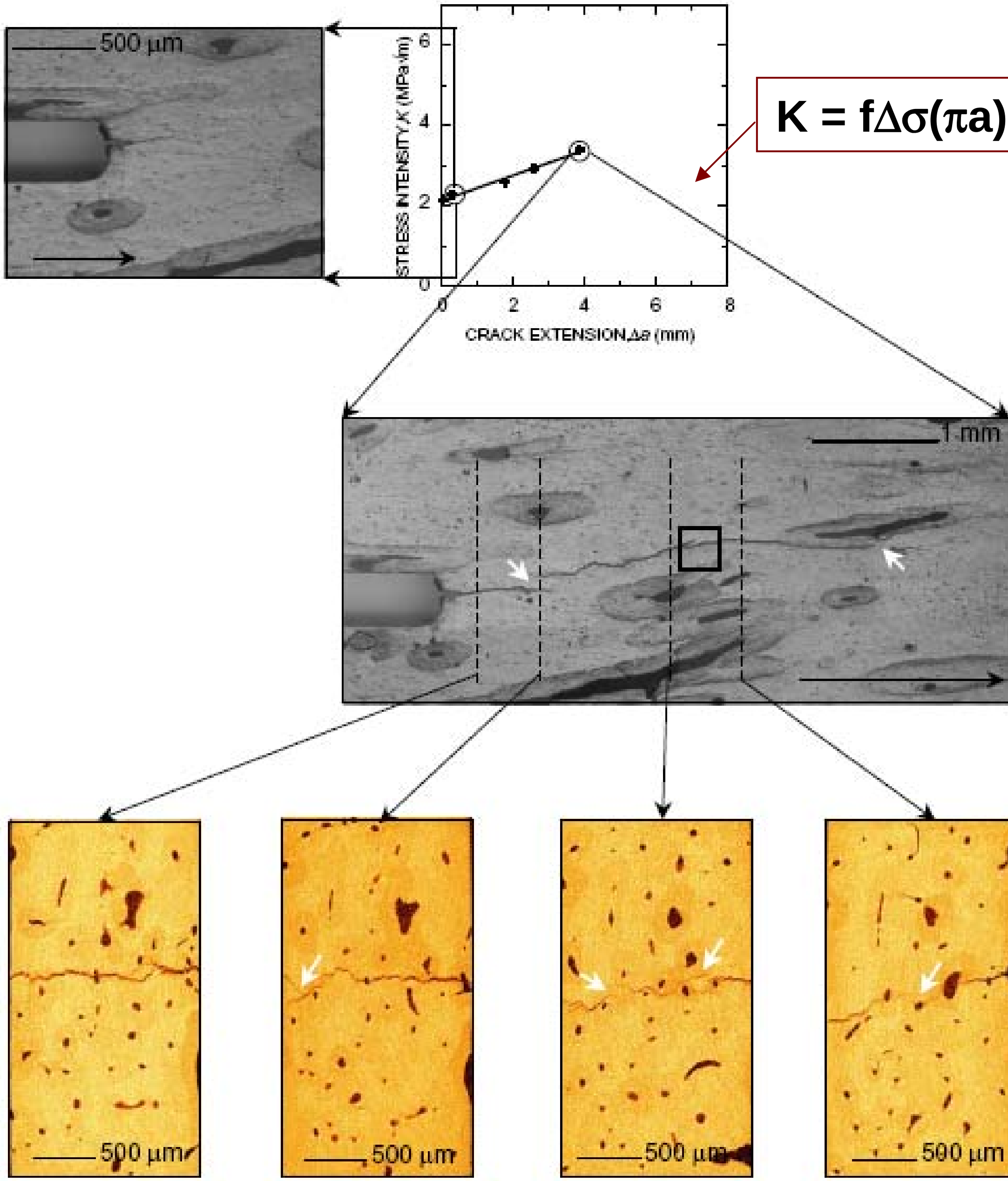
FRACTURE-TOUGHNESS MEASUREMENTS

Fracture-toughness testing was performed in general accordance with the ASTM Standard[31]. Tests were conducted using the notched three-point bending geometry with a span between the lower two loading points equal to 5–5.5 times the width of the beam. Longitudinal and transverse orientations were investigated. The notch was 'sharpened' by precracking using cyclic fatigue loading; this was achieved at a load ratio (ratio of minimum to maximum loads) of 0.1 and loading frequency of 2 Hz, with a final maximum stress intensity of K_{max} ~ 1–2 MPa $m^{1/2}$. The final precrack length (notch plus precrack) was generally ~0.4–0.6 *W*, with a presumed atomically sharp crack tip. Samples were then loaded to failure under displacement control with an ELF testing machine at ambient temperature at a cross-head displacement rate of 0.01 mm sec^{-1}. A record of the applied loads and the corresponding displacements was simultaneously monitored during the test and analysed to determine the fracture toughness. At least three separate specimens were tested for each orientation. Linear-elastic stress intensities, *K*, were computed from handbook solutions for three-point bending[31].

Image source: Nallaa, Kinney and Ritchie. Nature Materials 2 (2003).

optical micrograph of crack tip

$$K = f\Delta\sigma(\pi a)^{1/2}$$



3D tomography of osteons and cracks

Image source: Naza, Krulick, Kinney and Ritchie. Biomaterials 26 (2005) 217-226.

Cracks follow "cement line", or mineralized surface surrounding osteons.

3D tomographic reconstruction

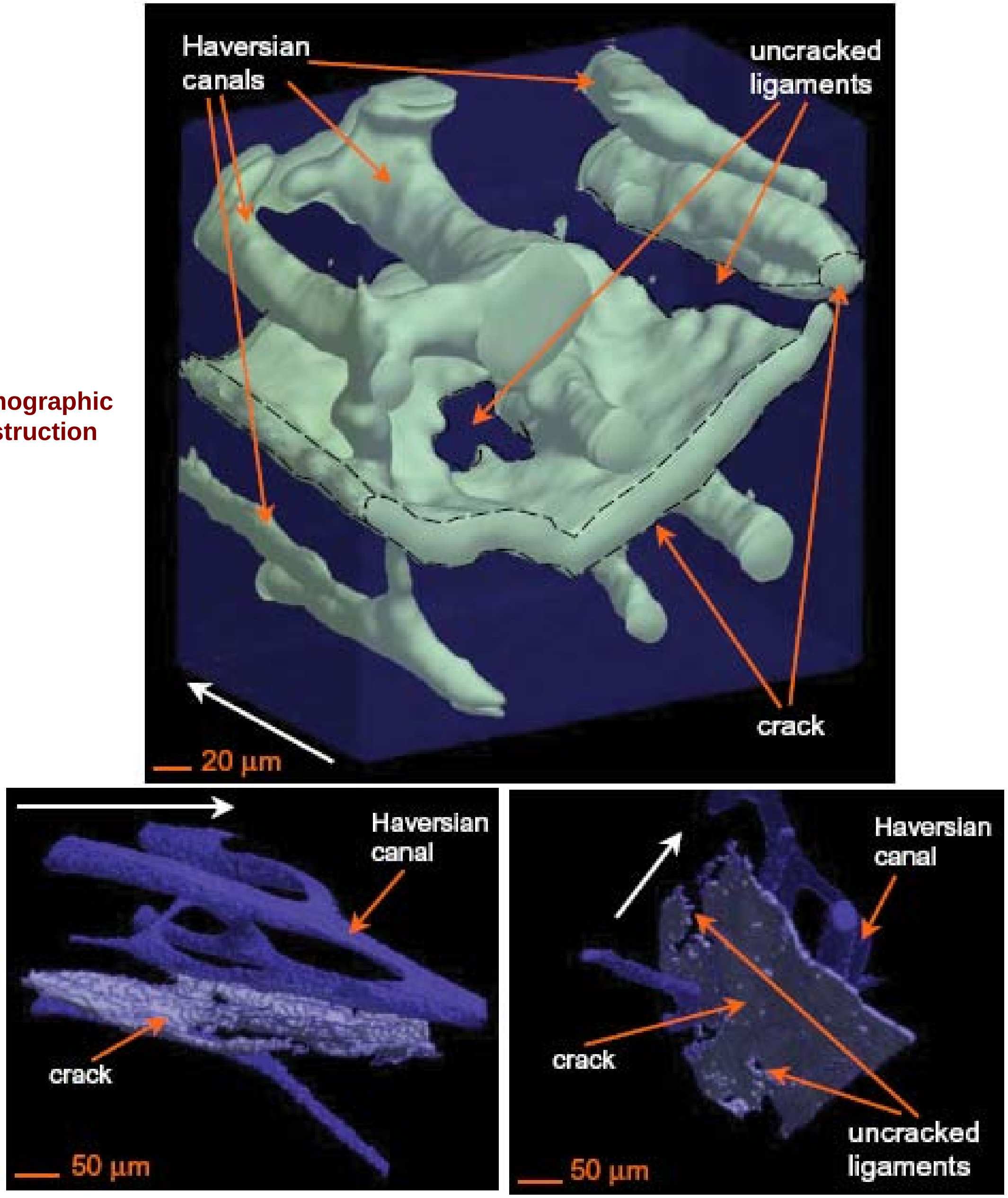


Image source: Naza, Krulick, Kinney and Ritchie. Biomaterials 26 (2005) 217-226.

Crack growth follows a Paris-law relation based in time: $\mathrm{d}a/\mathrm{d}t = AK^n$,

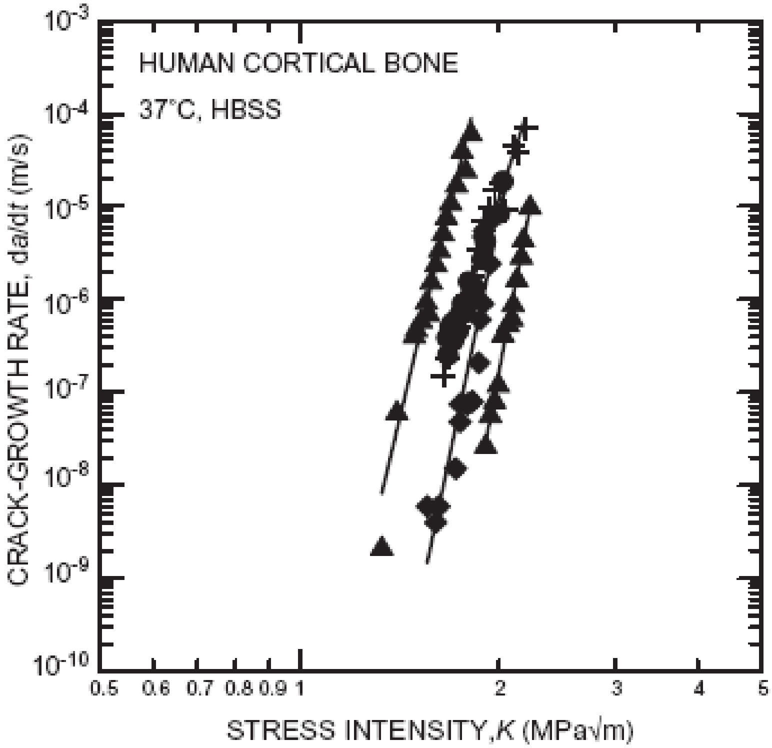


Fig. 8. Results showing the time-dependent subcritical crack-growth behavior of human cortical bone, in terms of the growth rates, $\mathrm{d}a/\mathrm{d}t$, as a function of the stress intensity, K, for growth rates $>10^{-9}$ m/s.

Conclusion:

Fig. 8 and Table 3 in Nalla, R. K., et al. "Mechanistic aspects of fracture and R-curve behavior in human cortical bone." Biomaterials 26 (2005): 217-231.

Image source: Naza, Krulick, Kinney and Ritchie. Biomaterials 26 (2005) 217-226.

Stress concentrations generate new cracks ahead of old cracks (bridging)

Image source: Naza, Krulick, Kinney and Ritchie. Biomaterials 26 (2005) 217-226.

How bone breaks:

Courtesy of R. O. Ritchie. Used with permission.

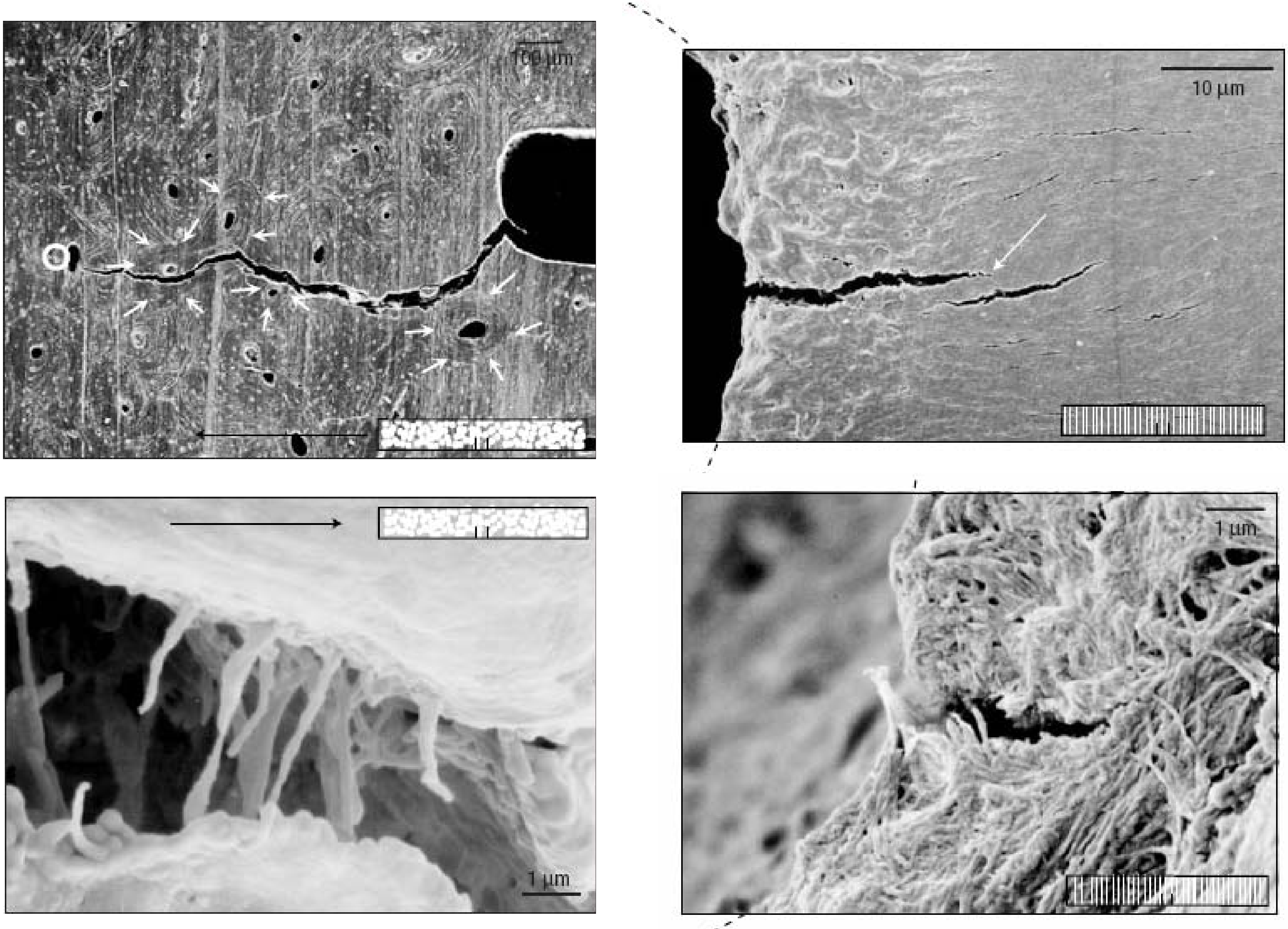


Image source: Nallaa, Kinney and Ritchie. Nature Materials 2 (2003).