On the Development of a Fracture Mechanics-Based Approach to Failure Prediction in Human Dentin # 1039

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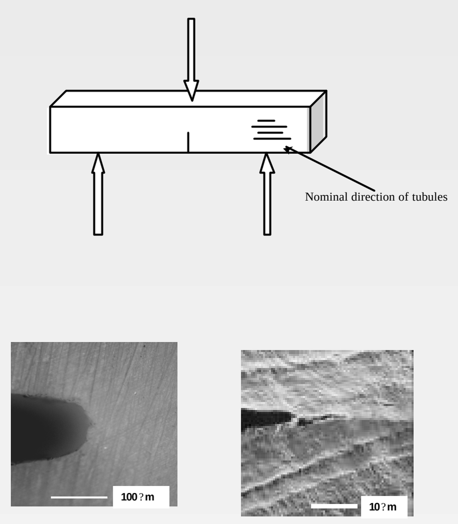
Objective:

There is a paucity of data on the fracture resistance of dentin that can be used to realistically predict failures. This study addressed this issue through a fracture-mechanics/mechanistic-based evaluation of the *in vitro* fracture toughness of dentin, and corresponding failures under cyclic loading. The objective was to establish a framework for life-prediction methodologies for human teeth in the presence of incipient cracks.

Background: Classical "S/N" Approach vs. Damage-Tolerant Approach

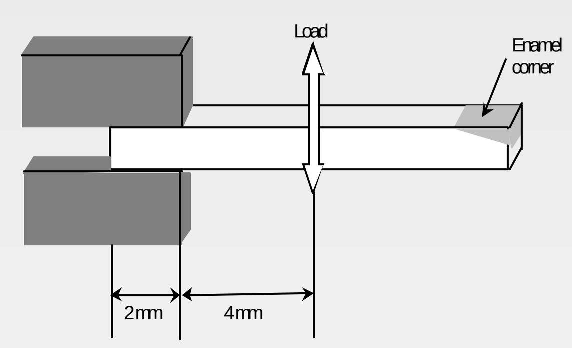
In engineering terms, fatigue refers to the response of a material to repeated application of stress or strain. The classical approach to fatigue has involved the characterisation of the total life to failure in terms of a cyclic stress range, and is often termed the "stress-life" or "*S/N*" approach. The measured fatigue lifetime represents the number of the cycles both to initiate and propagate a (dominant) crack to failure. However, in many structures including human teeth, where there is an inherent population of flaws, the crack initiation life may be essentially non-existent, thus making lifetimes predicted from the *S/N* approach highly non-conservative. The life may be considered solely as the number of cycles to propagate one such flaw to failure. To attempt life-prediction analysis, a fracture mechanics methodology is generally used (termed the damage-tolerant approach), where the number of cycles required for an incipient crack to grow subcritically to a critical size, defined by the limit load or fracture toughness, is computed from information relating the crack velocity to the mechanical driving force (e.g., the stress-intensity factor, *K*).

Experimental Set-up: Fracture Toughness



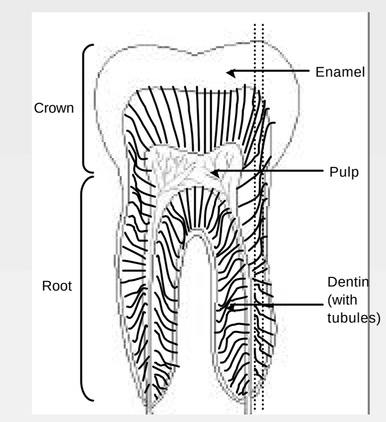
The three-point bending geometry used for fracture toughness tests is illustrated here. Each dentin beam tested included some root dentin and some coronal dentin. *In vitro* toughness tests were conducted in ambient temperature HBSS with unnotched cantilever beams cycled on an ELF? 3200 series acoustic testing machine (EnduraTEC Inc., Minnetonka, MN). Tests were conducted with blunt notches and sharp cracks to illustrate the effect of notch acuity.

Experimental Set-up: Fatigue



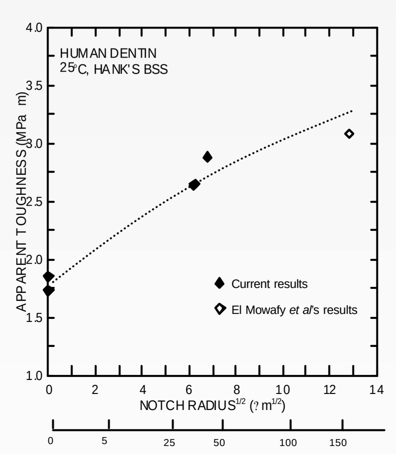
The cantilever beam geometry used for fatigue tests is illustrated here. Each dentin beam tested included some root dentin and some coronal dentin. *In vitro S/N* fatigue tests were conducted in ambient temperature HBSS with unnotched cantilever beams cycled on an ELF? 3200 series machine. Testing was performed at a range of load ratios, *R* (minimum load/maximum load) of -1 to 0.5 at cyclic frequencies between 2 and 20 Hz.

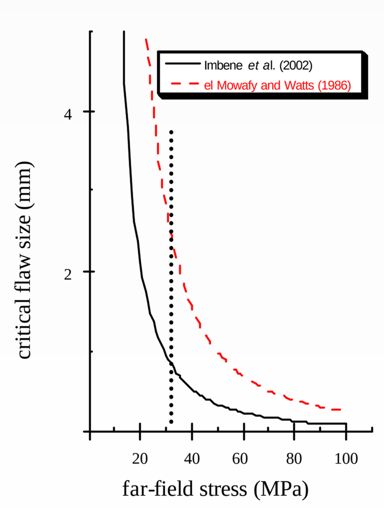
Experimental Set-up: Materials



Recently extracted human molars were used in this study. Each tooth was sterilised using gamma radiation after extraction. Sections, ~2.0 mm thick, were prepared from the central portion of the crown and the root in the bucco-lingual direction The dentin beams were then obtained from these sections by wet polishing up to a 600 grit finish.

Results: Fracture Toughness



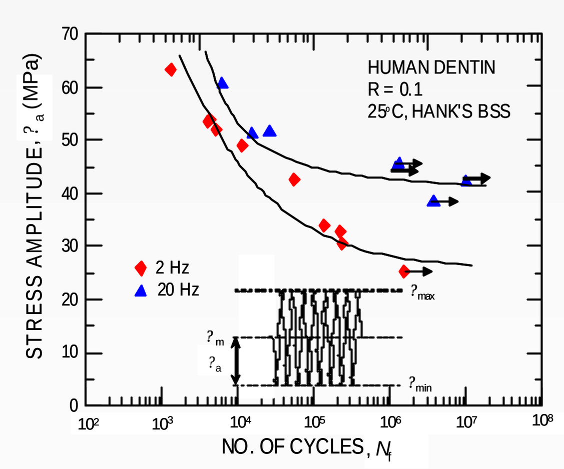


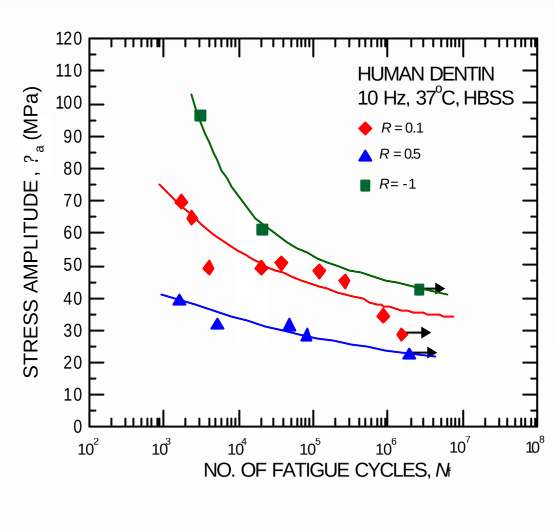
The fracture toughness was measured to be K_c = 1.79(?0.06) MPa?m.

The apparent toughness was shown to be directly proportional to the square root of the notch radius, and was increased by over 50% by using a sharp machined notch (with a 30-50 µm root radius) rather than a fatigue precrack.

Lower toughness implies reduction in predicted critical flaw size.

Results: *S/N* Fatigue





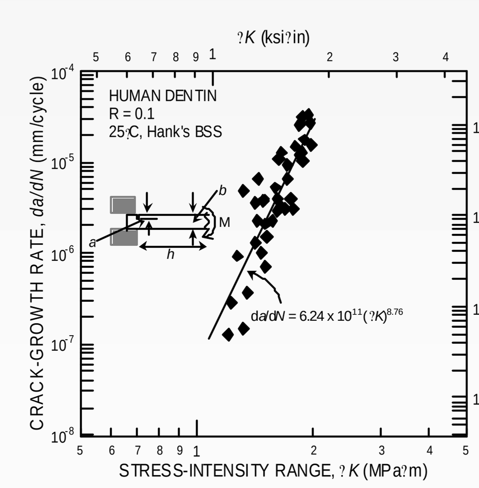
Existence of a fatigue response to repetitive loading in human dentin was demonstrated.

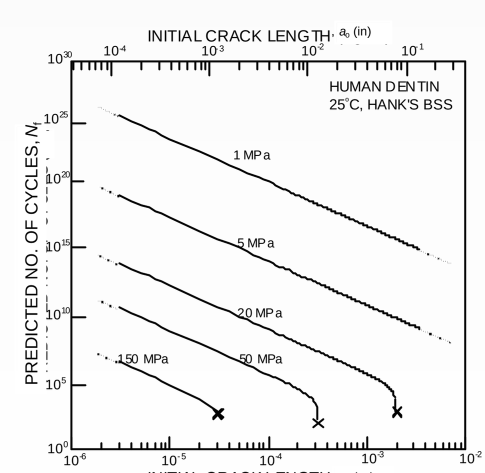
Dentin was observed to exhibit "metal-like" "Smooth-bar" stress-life (*S/N*) behavior with decreasing fatigue lives associated with increasing stress amplitude.

S/N curves displayed an apparent fatigue limit at 10^6-10^7 cycles, which was estimated to be ~25-45 MPa, depending on cyclic frequency.

Effect of mean stress/load ratio was observed, with increasing fatigue lifetimes with decreasing mean stress (*R* of 0.5 to *R* of -1) at any given stress amplitude.

Results: Fatigue Crack Growth

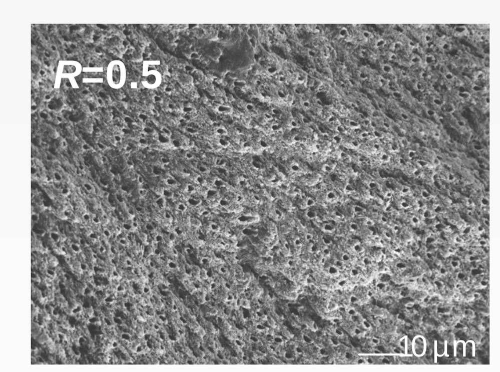


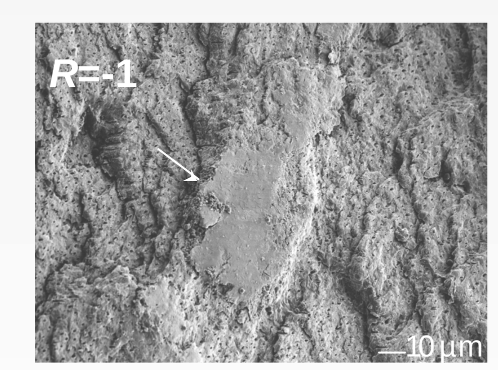


From the stiffness-loss during *S/N* tests, fatigue-crack growth rates, d*a*/d*N*, were determined and related to the stress-intensity range, ?*K*, suggesting a simple Paris power-law relationship, d*a*/d*N* ? ?K^m, with *m* ~ 8.76. Extrapolation to ~10^{-10} m/cycle yielded an estimated fatigue threshold of ?K_{TH}~1.06 MPa?m.

A framework for a fracture-mechanics based life-prediction methodology for the fatigue life was developed. Based on this preliminary analysis, small flaws in teeth of the order of 250 µm will not radically affect their structural integrity, as the projected lifetime exceeds that of the patient.

Results: Fractography





Scanning electron micrographs of the fracture surfaces obtained at different load ratios. Damage from the compressive segment of the fatigue cycle is obvious at *R* = -1.

Conclusions:

- A *worst-case* fracture toughness for dentin, perpendicular to the tubule orientation, has been measured as K_c = 1.8 MPa?m.
- Dentin also displays a susceptibility to *in vitro* fatigue, with a 10^6-10^7cycle fatigue limit of ~25-45 MPa at 2-20 Hz.
- The fracture mechanics based (*da/dN*) analysis was more conservative, with failure being predicted below the fatigue limit. Preliminary life-prediction calculations indicate that small (~250 µm) flaws will not radically affect the structural integrity of teeth.

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