UNDERSTANDING THE ROLE OF OSTEONS IN ARRESTING CRACKS IN CORTICAL BONES

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INTRODUCTION

The reasons behind the arrestment of microcracks in cortical bone are not completely understood. Two phases are assumed for the process of arresting a crack initiated in interstitial bone. In the first phase, the instability of the crack is increased, the crack propagation direction is changed, and the crack is attracted toward soft osteons.[1] In the second phase, once the crack reaches the osteon site, it is arrested at the cement line or somewhere inside the osteon. Experimental results and numerical analyses have both verified the phase one assumption.[1] In this work, we investigated how osteons can arrest cracks, as observed by us and others (Figure 1). We studied the influence of cement line thickness and modulus and intra osteon modulus on the stability of crack propagation.

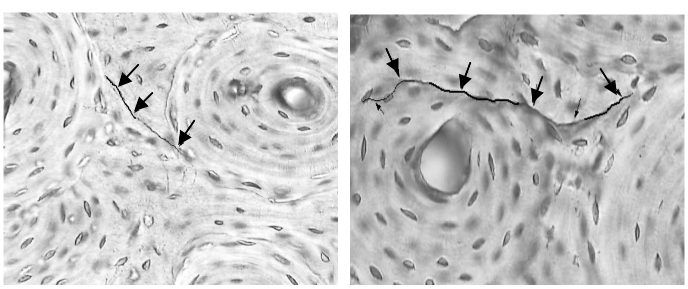

Figure 1. Typical microcracks (arrows) in cortical bone sections. Crack arrested at cement lines at both ends (left). One end of crack arrested at cement line and other end arrested within osteon (right).

TISSUE MICROSTRUCTURE OF OSTEONAL BONE

Osteonal bone consists of stiffer interstitial bone and softer osteons.[2] A typical osteon consists of a Haversian canal, intra osteon lamellae, and a cement line (Figure 1). The cement line is assumed to be the softest of these constituents. [3] The approximate diameter of an osteon is 200 μm. The cement line is 1 to 5 μm in width.

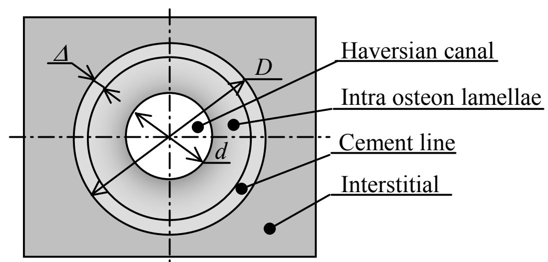

Figure 2. Structure of osteonal bone.

CRACK PROPAGATION IN OSTEONAL BONE

Herein we only consider crack propagation in planes perpendicular to the osteon's axis. All materials in the crack propagation plane are treated as isotropic. A square one-osteon model (Figure 3) is used to study the characteristics of crack propagation within an osteon. All cracks are assumed to be either in the cement line or the intra osteon lamellae area. Four possible initial horizontal cracks with length $2l$ at points a, b, m, n are considered. For each case only one of the four cracks exists.

The ratio of the side length (L) of the square plate to the external diameter (D) of the osteon is set to 10. The ratio of D to Haversian canal size d is set to 4, the ratio of all crack lengths $2l$ to D is set to 0.03, and the ratio of applied displacement δ to L is set to 0.01.

Let E_0, E_c, and E_i be Young's moduli of the three materials in the interstitial, cement line, and intra osteon areas, respectively. For the four possible cracks, we introduce the following normalized mode I stress intensity factors

$$a_{\mathrm{I\_l}} = \frac{K_{\mathrm{I\_left}}^{(a)}}{(E_0 \delta \sqrt{\pi l})/L} \tag{1}$$

$$a_{\mathrm{I\_r}} = \frac{K_{\mathrm{I\_right}}^{(a)}}{(E_0 \delta \sqrt{\pi l})/L} \tag{2}$$

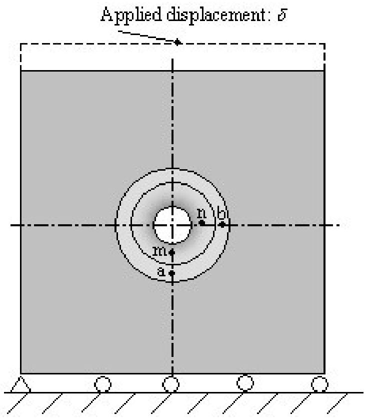

Figure 3. Infinite one-osteon plate model with four possible initial cracks with length 2*l* at a, b, m, n, respectively.

$$b_{\mathrm{I\_l}} = \frac{K^{(\mathrm{b})}_{\mathrm{I\_left}}}{(E_0 \delta \sqrt{\pi l})/L} \tag{3}$$

$$b_{\mathrm{I\_r}} = \frac{K^{(\mathrm{b})}_{\mathrm{I\_right}}}{(E_0 \delta \sqrt{\pi l})/L} \tag{4}$$

$$m_{\mathrm{I\_l}} = \frac{K^{(\mathrm{m})}_{\mathrm{I\_left}}}{(E_0 \delta \sqrt{\pi l})/L} \tag{5}$$

$$m_{\mathrm{I\_r}} = \frac{K^{(\mathrm{m})}_{\mathrm{I\_right}}}{(E_0 \delta \sqrt{\pi l})/L} \tag{6}$$

$$n_{\mathrm{I\_l}} = \frac{K^{(\mathrm{n})}_{\mathrm{I\_left}}}{(E_0 \delta \sqrt{\pi l})/L} \tag{7}$$

$$n_{\mathrm{I\_r}} = \frac{K^{(\mathrm{n})}_{\mathrm{I\_right}}}{(E_0 \delta \sqrt{\pi l})/L} \tag{8}$$

where K_{I} is mode I stress intensity factor, superscript a, b, m, and n refer to crack location, subscript left refers to the stress intensity factor of the left crack tip and subscript right refers to the corresponding parameter of the right crack tip.

When the Haversian canal size d = 0 and $E_c/E_0 = E_i/E_0 = 1$, $a_{\mathrm{I\_l}}$, $a_{\mathrm{I\_r}}$, $b_{\mathrm{I\_l}}$, $b_{\mathrm{I\_r}}$, $m_{\mathrm{I\_l}}$, $m_{\mathrm{I\_r}}$, $n_{\mathrm{I\_l}}$, and $n_{\mathrm{I\_r}}$ have a value of one. For general cases, the corresponding stress intensity factors K_{I} in Equations (1) to (8) are calculated by

$$K_{\mathrm{I}} = \sqrt{EG} \tag{9}$$

where E is Young's modulus of the surrounding material of the crack and G is the strain energy release rate, obtained through two finite element analyses (FE) using the same model but with two crack lengths differing by a small amount.[1] For each finite element analysis, an average number of 84,000 bilinear quadrilateral elements were used. Patran/Nastran was used to perform all FE analyses.

RESULTS

The corresponding normalized crack tip stress intensity factors for different cement line thickness Δ/D ratios and different E_c/E_0 and E_i/E_0 ratios are shown in Table 1, 2, and 3, respectively.

DISCUSSION AND CONCLUSION

Elastic properties of cement line and intra osteon and cement line thickness have a dramatic influence on the stability of crack propagation inside an osteon. With the decrease of cement line thickness and modulus, a crack within the cement line becomes very stable and the crack has the maximum instability in the circumferential direction (Table 1 and 2), which corresponds to many observations in bone (Figure 1). A crack inside the intra osteonal area still has a relatively high instability for different material properties and cement line thicknesses (Table 1, 2, and 3), and it is possible for a crack to propagate inside an osteon and be arrested there (Figure 1(b)). If the cement line is stiffer than the intra osteon, it becomes easy to arrest a crack inside an osteon (Table 3).

In conclusion, a crack can be arrested at the cement line for thin and soft cement line and a crack can be arrested inside an osteon for relatively thick and stiff cement line.

Table 1. Normalized crack tip stress intensity factors with respect to different cement line thickness ratios Δ/D for cement line modulus ratio E_c/E_0=0.1 and intra osteon modulus ratio E_i/E_0=0.35.

Δ/D	$a_{\mathrm{I\_l}}$	$a_{\mathrm{I\_r}}$	$b_{\mathrm{I\_l}}$	$b_{\mathrm{I\_r}}$	$m_{\mathrm{I\_l}}$	$m_{\mathrm{I\_r}}$	$n_{\mathrm{I\_l}}$	$n_{\mathrm{I\_r}}$
0.02	0.20	0.20	0.00#	0.00#	0.27	0.27	0.47	0.47
0.05	0.25	0.25	0.10	0.10	0.22	0.22	0.39	0.30
0.1	0.25	0.25	0.15	0.15	0.15	0.15	0.39	0.39
0.125	0.25	0.25	0.15	0.15	0.27	0.27	0.27	0.27
0.15	0.21	0.21	0.15	0.15	0.17	0.17	0.27	0.27

\# The ratio of crack length 2l to osteon diameter D was set to 0.018.

Table 2. Normalized crack tip stress intensity factors with respect to different cement line modulus ratios E_c/E_0 for cement line thickness ratio Δ/D=0.125 and intra osteon modulus ratio E_i/E_0=0.35.

E_c/E_0	$a_{\mathrm{I\_l}}$	$a_{\mathrm{I\_r}}$	$b_{\mathrm{I\_l}}$	$b_{\mathrm{I\_r}}$	$m_{\mathrm{I\_l}}$	$m_{\mathrm{I\_r}}$	$n_{\mathrm{I\_l}}$	$n_{\mathrm{I\_r}}$
0.05	0.18	0.18	0.02	0.02	0.15	0.15	0.27	0.27
0.1	0.25	0.25	0.15	0.15	0.27	0.27	0.27	0.27
0.2	0.29	0.29	0.29	0.29	0.19	0.19	0.39	0.39
0.3	0.36	0.36	0.44	0.44	0.19	0.19	0.47	0.47
0.4	0.29	0.29	0.51	0.51	0.19	0.19	0.47	0.47

Table 3. Normalized crack tip stress intensity factors with respect to different and intra osteon modulus ratios E_i/E_0 for cement line thickness ratio Δ/D=0.125 and cement line modulus ratio E_c/E_0 =0.1.

E_i/E_0	$a_{\mathrm{I\_l}}$	$a_{\mathrm{I\_r}}$	$b_{\mathrm{I\_l}}$	$b_{\mathrm{I\_r}}$	$m_{\mathrm{I\_l}}$	$m_{\mathrm{I\_r}}$	$n_{\mathrm{I\_l}}$	$n_{\mathrm{I\_r}}$
0.05	0.11	0.11	0.15	0.15	0.04	0.04	0.10	0.10
0.15	0.15	0.15	0.15	0.15	0.18	0.18	0.25	0.18
0.25	0.21	0.21	0.15	0.15	0.12	0.12	0.33	0.33
0.35	0.25	0.25	0.15	0.15	0.27	0.27	0.27	0.27
0.45	0.29	0.29	0.10	0.10	0.22	0.22	0.44	0.44

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