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Transverse fracture of canine teeth

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ABSTRACT

The critical conditions to effect transverse fracture in canine teeth of carnivores in lateral loading are analyzed. The teeth are modeled as tapered coaxial beams with uniformly thin enamel coats. A stress analysis is first carried out using beam theory, and stress intensity factors for inward propagating cracks at the location of maximum tensile stress along the lingual face are then determined. The fracture begins as arrested channel cracks within the enamel, followed by stable penetration around the tooth and into the dentin to the point of failure. Two- and three-dimensional finite element models are used to evaluate the full fracture evolution. The analysis yields an explicit scaling relation for the critical fracture load in terms of characteristic tooth dimensions, notably tooth height and base radius. The role of enamel, ignored in previous 'strength of materials' analyses, is shown to be important in determining the precursor crack equilibrium prior to full fracture. Implications concerning allometry are briefly discussed.

1. Introduction

There has been considerable interest in the strength and durability of mammalian teeth, in particular how much bite force can be sustained without fracture. The bulk of attention has been given to molar teeth of humans, hominins and other mammals with flat, rounded (bunodont) molars (Janis and Fortelius, 1988; Popowics et al., 2001, 2004; Lucas, 2004; Lucas et al., 2008; Chai et al., 2009b; Lawn et al., 2009; Constantino et al., 2010; Lee et al., 2010, 2011; Ungar, 2010; Barani et al., 2011). In these cases the most common form of fracture is by longitudinal cracking in near-axial loading, in which a 'channel' crack runs vertically up or down within the enamel shell wall. But there has also been some consideration of mammals with elongate teeth, e.g. carnivores (van Valkenburgh and Ruff, 1987; van Valkenburgh, 1988; Freeman and Lemen, 2007a, 2007b) and herbivores (Damuth and Janis, 2011). In those cases longitudinal fracture is largely suppressed (Barani et al., 2012b), opening up the possibility of fracture by an alternative, transverse cracking mode, especially from laterally applied forces. Interspecies comparisons are vital in determining evolutionary paths for tooth morphologies in relation to diet—how these morphologies are constrained by the capacity to sustain high bite force and how some teeth evolve to adapt to changing food sources. In carnivores, a prime consideration is a potential trade-off between tooth strength and tooth penetration with elongation (Evans and Sanson, 1998; Freeman and Lemen, 2007b).

Transverse fractures in canines are indeed prevalent in canine teeth (van Valkenburgh and Ruff, 1987; van Valkenburgh, 1988). The critical conditions to produce such fractures have previously been analyzed using a 'strength of materials' approach, representing the tooth as a cantilever beam in flexure loaded laterally at some point along its lingual (tongue-side) face (Freeman and Lemen, 2007a, 2007b). This earlier approach used finite element methods (FEM) to model a generic tapered and curved canine geometry subjected to an applied bending moment. Side and section views of canines from a range of wild-caught carnivores (coyote, red fox, bobcat, raccoon), along with fracture tests on intact specimens, were used to provide data for computational comparison (Freeman and Lemen, 2007a). Fracture was considered to occur when the maximum tensile stress in the dentin exceeds some limit—an 'effective strength'. However, these earlier attempts did not consider the way in which a crack initiates and propagates through the enamel into the dentin and thence to failure. Moreover, no explicit relation expressing the critical bite force in terms of characteristic tooth dimensions and material properties was determined.

In this paper we present a fracture mechanics analysis of transverse fracture in canine teeth. We begin by considering the tooth morphology to be that of a tapered coaxial beam of elliptical cross section, with uniformly thin enamel coat. Traditional beam theory is used to determine the maximum tensile stresses within the flexurally loaded tooth. Stress intensity factors are then derived for inward penetrating cracks within the flexural stress

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field. We demonstrate that fractures first form as channel cracks in the enamel, arrest at the dentin–enamel interface, and then penetrate into the dentin before becoming unstable. This description is consistent with the observation of multiple channel ('hairline') cracks in the enamel of canine teeth (spacing ~0.5 mm in coyote) prior to fracture (Freeman and Lemen, 2007a). Two- and three-dimensional finite element models are used to validate the fracture mechanics description and to provide clearer insight into the fracture evolution. A simple scaling equation for the critical force to produce failure in canine teeth is derived, expressed explicitly in terms of tooth base radius and height. This equation is of particular interest in the context of 'allometry', i.e. understanding how the critical fracture force scales with tooth or body size within different carnivores (Wroe et al., 2005; Freeman and Lemen, 2007a; Wroe, 2008; Chamoli and Wroe, 2011).

2. Materials and methods

2.1. Canine geometry and properties

Fig. 1a shows a computed tomography image of a canine within the skull of an adult male lion. The tooth is deeply anchored within the jawbone. There is a certain geometrical similarity in the shape of canines for a broad range of extant cats, dogs and other mammals, with ratio of height to jawline base radius varying within 3–5 (Freeman and Lemen, 2007a). Fig. 1b is a schematic representation, treating the tooth as a tapered coaxial beam of height H, radii r and R at cusp and base, fixed enamel thickness d, and clamped at its base. The cross section is elliptical, with minor/major radius ratio λ constant along its length. The enamel is typically thin in carnivores, slightly less than 1 mm in the case of lion. A force P is applied laterally along a major diagonal at a specified distance L from the base. For the present we ignore the curvature of the tooth along its length and omit the pulp cavity, but include the latter feature in a following analysis using 'extended finite element modeling'.

No systematic studies appear to have been reported for the material properties of canine teeth in carnivores. Accordingly, we rely on values taken from human teeth, with some suggestions that interspecies variations may not be substantial (Lee et al., 2010; Constantino et al., 2012) but mindful that absolute predictions of critical fracture loads will be subject to some uncertainty. For elastic properties, we assume a fixed ratio $E_e/E_d = 90\ \mathrm{GPa}/18\ \mathrm{GPa} = 5.0$, where E is Young's modulus (Barani et al., 2011, 2012b). Strictly, modulus values can vary across the enamel and dentin thickness (Cuy et al., 2002; Darnell et al., 2010; Lee et al., 2010; Barani et al., 2012a), and can change with tooth orientation (Spears, 1997). For fracture properties, we take toughness $T_e = 1.5\ \mathrm{MPa\ m^{1/2}}$ (resistance to crack propagation, or critical 'stress intensity factor', with dimensions of stress × crack length$^{1/2}$) for cracks crossing prisms within the enamel (Xu et al., 1998) and $T_d = 3.0\ \mathrm{MPa\ m^{1/2}}$ for cracks within dentin (Koester et al., 2008). In reality, the toughness of enamel and dentin can increase with continued crack extension (R-curves), but we simply take values corresponding to well-developed cracks.

2.2. Flexural stresses in coaxial beam

We begin by calculating stresses σ in the enamel coat at any point x along the tooth axis. The corresponding tooth radius $b(x)$ in Fig. 1b varies linearly between $b = R$ at $x = 0$ and $b = r$ at $x = H$. Straightforward beam theory yields the tensile stress at x on the loaded edge of the enamel:

$$\sigma_e(x) = 4P(L-x)/\kappa\pi b^3 \tag{1}$$

with κ a dimensionless modification factor (Chantikul et al., 1979):

$$\kappa(x) = \lambda[1-(1-E_e/E_d)(1-d/b)^4] \tag{2}$$

These equations enable maximum tensile stresses σ_m to be computed along the coordinate x for any given tooth dimensions.

2.3. Fracture mechanics

Consider a crack of depth c penetrating through an enamel layer of thickness d into a thick dentin sublayer. Suppose the cracks start at the location of maximum stress $\sigma_e = \sigma_m$ along the lingual tooth edge. The stress intensity factor for such a crack within the enamel/dentin bilayer can be written as

$$K = \sigma_m c^{1/2} F(c/d) \tag{3}$$

where $F(c/d)$ is a dimensionless factor allowing for the modifying effect of elastic mismatch between enamel and dentin (Fett and Munz, 1997). An estimate of $F(c/d)$ may be obtained by considering a single edge crack in a rectangular bilayer specimen with thin brittle coating of thickness d and thick substrate ($d \ll R$) subjected to a uniform tensile strain $\varepsilon = \sigma_e/E_e = \sigma_d/E_d$ parallel to the surface. Such a strain condition approximates that of a flexural field for thin enamel layers, where strain gradients on either side of the DEJ are minimal. We then use a routine 2D finite element model (FEM) (ANSYS Version 6.0, ANSYS Inc, Cannonsburg, PA) to compute the stress field about the crack for specified values of c within the enamel or dentin, and an Irwin crack-opening displacement formulation to evaluate the appropriate stress intensity factor function $K(c/d)$ (Lawn, 1993). Crack extension occurs when K exceeds the toughness of the enamel (T_e) or dentin (T_d). Critical fracture loads may then be determined for cracks attaining an unlimited instability condition.

The same approach is used to evaluate $K(c/d)$ for a specimen containing multiple parallel cracks of uniform spacing w (Chai and Fox, 2012).

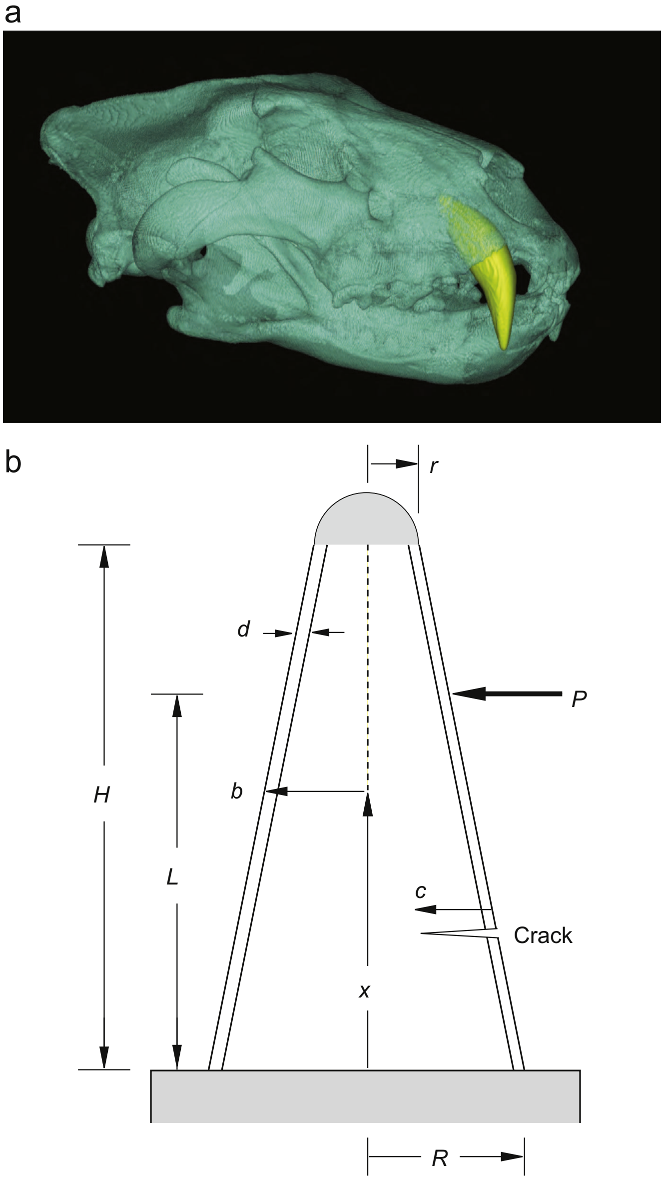

Fig. 1. Canine teeth in carnivores. (a) Computed tomography scan of lion skull, highlighting canine. Tooth is anchored deep within jawbone. Courtesy S. Wroe. (b) Schematic representation indicating characteristic dimensions of generic conical canine tooth model. Tooth is loaded with force P laterally along side wall at distance L from base, causing flexure with consequent incidence of transverse crack. Base is considered 'built-in' to jaw.

2.4. Extended finite element modeling

An objective means of validating the beam analysis, as well as providing an instructive 3D visualization of the transverse fracture process, is provided by extended finite element modeling (XFEM; Abaqus 6.9-EF1, Simulia, Providence, RI).