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Mechanics analysis of molar tooth splitting

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ABSTRACT

A model for the splitting of teeth from wedge loading of molar cusps from a round indenting object is presented. The model is developed in two parts: first, a simple 2D fracture mechanics configuration with the wedged tooth simulated by a compact tension specimen; second, a full 3D numerical analysis using extended finite element modeling (XFEM) with an embedded crack. The result is an explicit equation for splitting load in terms of indenter radius and key tooth dimensions. Fracture experiments on extracted human molars loaded axially with metal spheres are used to quantify the splitting forces and thence to validate the model. The XFEM calculations enable the complex crack propagation, initially in the enamel coat and subsequently in the interior dentin, to be followed incrementally with increasing load. The fracture evolution is shown to be stable prior to failure, so that dentin toughness, not strength, is the controlling material parameter. Critical conditions under which tooth splitting in biological and dental settings are likely to be met, however rare, are considered.

1. Introduction

Teeth are brittle and subject to fracture. Several fracture modes have been identified and analyzed, including longitudinal (‘radial’ or ‘margin’) cracking [1–8], edge chipping [9,10] and transverse fracture [11–14]. At normal biting forces, i.e. well below 1 kN in humans, each of these crack types remains contained entirely within the enamel. Dentists tend to consider such contained enamel cracks as incidental, without the need for restoration [15]. Biologists, on the other hand, regard crack patterns as valuable indicators of dietary history in a wide range of extinct hominins and extant (living) mammals [16], and use them to quantify bite forces [17]. The fractures become more serious when the tooth experiences an uncommonly severe overload: longitudinal cracks in near-axial loading can penetrate into the dentin and run through to the tooth base to cause an entire molar or premolar to split [9]; chipping cracks can run to the enamel–dentin interface, causing a large fragment of a tooth to spall away [9]; transverse cracks, most notably in canines under lateral loading, can penetrate directly into the subterranean dentin and break off a large portion of the tooth [13]. All these cracks extend incrementally with increasing load, indicating an inherently stable failure evolution. Without dental intervention, such failures can severely compromise oral function.

The splitting mode is of interest to clinicians, for it necessitates radical dental therapy, more often entire tooth replacement than remedial restoration. No systematic attempt to evaluate the mechanics of this fracture mode has previously been made. Empirical fracture tests with centrally loaded hard spheres on extracted human molars and cylinders on premolars confirm abnormally high critical splitting loads, in the range 1.3–2.5 kN [18–20]. These studies note that an imperfect restoration can diminish this load by as much as a factor of 2, consistent with clinical experience [15,21,22]. Analogous studies on all-ceramic pre-molar crowns indicate comparable splitting loads [23]. However, it is difficult to systemize the data, as tooth dimensions and experimental conditions are not usually included. From a theoretical standpoint, many studies have been made of stress distributions in loaded teeth using conventional finite element modeling (FEM) codes [24–32], but these can say virtually nothing about how stable fractures evolve. They certainly cannot account for any stages of crack arrest in the enamel and subsequent penetration into the dentin interior [13]. For this it is necessary to resort to more advanced finite element modeling with the mesh containing an embedded crack, so that the fracture can be followed step-by-step through the tooth complex [5–8]. Accordingly, a detailed analytical approach, validated by experimental data, is called for.

In this paper we adopt such an approach. First, we conduct experimental fracture tests on extracted human molars with hard spherical indenters and document the effect of sphere radius on

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the critical splitting load. Then we develop a simple 2D fracture mechanics analysis based on a wedged cusp model, resulting in an explicit equation for critical splitting load in terms of sphere radius and tooth dimensions. A so-designated 'Extended Finite Element Method' (XFEM) with an embedded crack is then used to validate the analysis and to account for geometrical detail, most notably 3D crack propagation through the dentin underlayer. Our focus here is on human molars, but the methodology extends to other mammals with similar flat, low-crowned (bunodont) teeth. Dental issues associated with high bite forces, and dietary implications in different mammalian species, will be considered.

2. Experimental study of tooth splitting

2.1. Materials and methods

As in an earlier study [9], human molar teeth extracted from patients aged 20–30 years old were supplied to us in aqueous solution by the American Dental Association laboratories at the US National Institute of Standards and Technology (NIST), with full patient consent and in accordance with IRB approved protocol. Lower second molars from this supply were cleaned and examined under a stereo microscope to exclude those with excessive pre-existing cracks, geometric abnormality, discoloration, or caries. Table 1 shows typical variation in base tooth radius (one half mean of maximum distal/mesial and buccal/lingual diameter) and height (top of most prominent cusp to enamel margin). The selected specimens were kept in distilled water prior to testing.

The roots of the teeth were sawn with a diamond-impregnated disk transversely to the vertical axis 2 mm below the enamel terminus to provide flat bases. The cut surfaces were then placed on a metal platen and loaded axially with tungsten carbide spheres placed freely at the central fossa. The spheres were pressed by another metal platen at a rate of 0.1 mm min^{-1} using a standard loading frame operated in displacement-control mode. Four ball radii were used: 0.78, 1.57, 1.98 and 2.37 mm.

A video camera equipped with a telescopic lens was used to observe the evolution of tooth fracture during the loading process [3]. Longitudinal cracks were observed to grow steadily along the enamel side walls with increasing load, either downward from the occlusal surface (radial cracks) or upward from the enamel base (margin cracks) [2,5,33]. At higher loads, well after the completion of longitudinal fracture, the test machine load–displacement curve began to flatten out before abruptly dropping to zero, at which point the tooth split. Splits at lower critical loads occurred near-symmetrically in the valleys between prominent cusps, whereas some at higher critical loads split into quarters. With larger spheres, some premature edge chipping occurred, with attendant secondary load drops, prior to splitting.

2.2. Experimental results

Fig. 1 typifies the general splitting morphology. Fig. 1a is an image of an *in vivo* split premolar [15]. This tooth is clinically 'dead', necessitating replacement. Fig. 1b is a top-surface view of an extracted molar indented *ex vivo* with a sphere of radius 0.78 mm at a critical load 1562 N, and Fig. 1c is a corresponding side view. The split has created two near-symmetrical segments. Fig. 1d is a top-surface view of a molar indented with a sphere of radius 1.98 mm at a critical load 3058 N. In this last case the tooth has segmented into three pieces. Comparison between the critical loads pertaining to (b) and (d) suggests a diminished wedging action of the larger sphere. The visual resemblance between the clinical example in (a) and the laboratory examples in (b), (c) and (d) is apparent. Indentations with spheres of radii larger than 4 mm tended to produce edge chipping rather than splitting, and on occasion even caused delamination of the enamel from the underlying dentin.

More detailed critical load data on individual molar teeth are included in Table 1, for four indenting sphere radii. The data show considerable scatter, suggesting that the indenter may not always make contact with all cusp walls. Despite the scatter, the mean critical loads show a clear trend toward higher values with increasing sphere radius. In all cases the splitting loads are well above the nominal biting force (<1 kN) for human molars.

3. Splitting model and analysis

3.1. Analytical model

We begin with the simplistic analytical model of a molar tooth in Fig. 2, with the goal of determining an analytical relation for the critical splitting force in terms of key indenter and tooth dimensions. The model consists of four truncated hemispherical cusps of radius $r_c = R/2$ on a cylindrical base of radius R, so that opposite neighbors just touch each other and adjacent neighbors share a

Table 1
Data from *ex vivo* splitting tests on human molars. Calculated mean coefficient C in Eq. (3) is listed for each group at right.

Sphere radius r (mm)	Tooth radius R (mm)	Tooth height H (mm)	Critical load P_S (N)	Constant C (Mean ± SD)
0.78	5.1	8.9	1562	1.29 ± 0.06
0.78	4.7	9.2	1612	
0.78	5.1	10.3	1601	
1.57	5.3	7.5	2606	1.37 ± 0.41
1.57	5.4	7.9	3051	
1.57	5.7	7.5	2020	
1.57	5.5	7.9	3403	
1.57	5.3	7.3	2221	
1.57	5.3	8.3	2035	
1.57	4.7	7.5	1580	
1.98	5.9	9.5	3069	1.32 ± 0.12
1.98	5.5	9.9	3129	
1.98	5.1	7.7	3058	
1.98	5.9	8.3	2007	
1.98	5.2	9.5	3159	
2.37	5.6	7.7	3163	1.49 ± 0.21
2.37	5.7	8.3	3238	
2.37	5.1	7.8	3855	