JOURNAL OF THE MECHANICAL BEHAVIOR OF BIOMEDICAL MATERIALS 35 (2014) 85–92

Available online at www.sciencedirect.com

ScienceDirect

www.elsevier.com/locate/jmbbm

Research Paper

Role of multiple cusps in tooth fracture

Amir Barani[a], *Mark B. Bush*[a,*], *Brian R. Lawn*[a,b]

[a]*School of Mechanical and Chemical Engineering, The University of Western Australia, WA 6009, Australia*
[b]*Materials Measurement Laboratory, National Institute of Standards and Technology, Gaithersburg MD 20899, USA*

ARTICLE INFO

Article history:
Received 4 December 2013
Received in revised form
18 March 2014
Accepted 27 March 2014
Available online 3 April 2014

Keywords:
Molar teeth
Fracture evolution
Multicusp
Critical load

ABSTRACT

The role of multiple cusps in the biomechanics of human molar tooth fracture is analysed. A model with four cusps at the bite surface replaces the single dome structure used in previous simulations. Extended finite element modelling, with provision to embed longitudinal cracks into the enamel walls, enables full analysis of crack propagation from initial extension to final failure. The cracks propagate longitudinally around the enamel side walls from starter cracks placed either at the top surface (radial cracks) or from the tooth base (margin cracks). A feature of the crack evolution is its stability, meaning that extension occurs steadily with increasing applied force. Predictions from the model are validated by comparison with experimental data from earlier publications, in which crack development was followed in situ during occlusal loading of extracted human molars. The results show substantial increase in critical forces to produce longitudinal fractures with number of cuspal contacts, indicating a capacity for an individual tooth to spread the load during mastication. It is argued that explicit critical force equations derived in previous studies remain valid, at the least as a means for comparing the capacity for teeth of different dimensions to sustain high bite forces.

1. Introduction

The human molar bites with sufficient force to break down and process an enormous variety of foods (Lucas, 2004; Ungar, 2010). However, high bite forces can cause the tooth enamel to fracture by longitudinal cracking along the side walls (Lucas et al., 2008; Lawn and Lee, 2009; Barani et al., 2011; Lee et al., 2011; Lawn et al., 2013). Longitudinal fractures may radiate from the occlusal surface down to the enamel margin (radial R cracks), or conversely from the margin to the occlusal surface (margin M cracks), all the while remaining confined within the enamel coat in the form of 'channel' fissures (Chai et al., 2009b; Barani et al., 2011; Keown et al., 2012b). Secondary chipping, and even splitting, can occur (Constantino et al., 2010; Chai et al., 2011). The longitudinal fracture mode is of special interest for its frequency of occurrence and its potential as a precursor to spallation of the enamel from the dentin in occlusal overloads (Popowics et al., 2001; Qasim et al., 2005), i.e. as a 'failure' condition. A fundamental understanding of the morphology of longitudinal cracking in multicusp structures, along with the capacity to predict the critical loads as a function of key geometrical parameters, is of particular relevance to dentistry and biology (Lucas et al., 2008).

Substantial advances have recently been made in the understanding of longitudinal cracks through experimental observation of fractures in axially loaded epoxy-filled glass-shell models (Qasim et al., 2005, 2006a, 2006b, 2007) and in extracted molar

*Corresponding author.

http://dx.doi.org/10.1016/j.jmbbm.2014.03.018
1751-6161/

teeth (Lawn et al., 2009; Lee et al., 2009, 2011; Chai et al., 2011; Keown et al., 2012b). Critical load data for longitudinal fractures on cusp-loaded molar teeth show considerable scatter, typically between 500 N and 1000 N, reflecting natural variations in tooth size and shape (Lee et al., 2009; Keown et al., 2012b). Mathematical modelling of the fracture process in shell structures has yielded simple but powerful explicit equations for the prediction of critical fracture loads in terms of key geometrical dimensions, notably tooth radius, tooth height and enamel thickness (Rudas et al., 2005; Chai et al., 2009b; Lawn and Lee, 2009; Barani et al., 2011, 2012b). Predictions from these equations have been used to provide an upper bound to the experimental critical load data on human molars (Lee et al., 2011).

A criticism of the structural models used to simulate the cuspal configuration of molar tooth fracture is the simplicity of the geometrical representation, that of a single hemispherical dome on a short cylindrical base. In reality, many teeth have multiple cusps. Human molars in particular have four (sometimes five) cusps, while premolars have two (Kono et al., 2002; Benazzi et al., 2013). A human molar is shown in Fig. 1. Other mammals have different cusp structures, some more and some less convoluted (Ungar, 2010). Previous justification for the use of the simple dome structure is that it accounts for the main features of the experimentally observed crack development, most notably full containment of the crack within the enamel wall (i.e. without penetrating into dentin) and a largely stable extension to full fracture with progressively increasing axial load (Chai et al., 2009b; Barani et al., 2011, 2012b). It also facilitates derivation of the critical load equations with minimal complication, enabling quantitative prediction of bite force (Lee et al., 2011). Nevertheless, the case for a significant role of a multiple cusp geometry remains to be answered. Relevant to the argument is the reported observation on glass shell structures that the critical force for fracture diminishes as the load point is shifted further from the central axis, by a factor of two or more (Qasim et al., 2006b). The presence of multiple cusps also provides the potential for spreading the applied load over more than a single cusp, and the possibility that an object located between cusps may generate a wedging force driving cracks along the cuspal 'valleys' (DeLong and Douglas, 1983).

Fig. 1 – Image of human molar tooth, showing cusp geometry at occlusal surface. Courtesy Paul Abbott.

The aim of this paper is to determine the role of multiple cusps in the incidence of longitudinal fracture, and specifically to examine how any differences in crack response affect the previously determined critical load equations. We replace our preceding single-dome model of a human molar with that of a four-cusp enamel cap. In reality, the molar tooth morphology in humans and other primates is more complex (Yamashita, 1998; Kono et al., 2002; Smith et al., 2005; Benazzi et al., 2013; Berthaume et al., 2013; Frunza and Suciu, 2013), but in the interest of computational simplicity we assume the individual cusps to be hemispherical and equispaced. It will be argued that this idealization is not restrictive, since ultimate failure is governed by the stress state over the entire longitudinal crack path and not at local geometrical features. An extended 3D finite element model (XFEM) described in preceding publications, with provision for incremental crack extension embedded into the XFEM code, is used to determine this ultimate failure condition (Barani et al., 2011, 2012b). While traditional finite element analyses have been employed extensively to map out stress distributions in occlusally loaded molar teeth (Yettram et al., 1976; Rubin et al., 1983; Spears et al., 1993; Wakabayashi et al., 2008; Tajima et al., 2009; Anderson et al., 2011; Anderson and Rayfield, 2012; Benazzi et al., 2012, 2014), such analyses lack capacity to predict the critical loads at full failure. Using the XFEM methodology, we examine various loading and crack alignment configurations, and compare and contrast the results with those from previous, single-dome studies.

2. Methods

The multicusp molar model is shown at left in Fig. 2, along with the former single-dome model at right. In each case the structure consists of an enamel shell of thickness $d=1.0$ mm, base radius $R=5.0$ mm and height $H=7.5$ mm, bonded to a dentin interior. These are nominal values—actual values vary considerably in real molar teeth, by as much as a factor of two (Keown et al., 2012b). Simple scaling relations exist for predicting critical conditions for tooth enamel of different dimensions (Barani et al., 2011), so our choice of values is not limiting. The hemisphere radius in the four-cusp configuration is $r=2.5$ mm, with smoothed-out valleys between.

The structures in Fig. 2 were configured using XFEM implemented in Abaqus (Abaqus 6.9-EF1, Simulia, Providence, RI). Details of the procedure have been described previously (Barani et al., 2011, 2012a, 2012b). A full 3D analysis was necessary to deal with off-axis loading. The structures were mounted on a frictionless flat surface and anchored at the mid-point of the base to resist any lateral forces. A finite element mesh was constructed, with higher density along the prospective crack plane, and refined until the calculations converged. Frictionless contacts were applied using a flat plate loaded normally onto one or more cusps, as shown in Fig. 3. Properties for the enamel (e) and dentin (d) were assumed to be homogeneous and isotropic in each material. Nominal values were taken from previous studies (Barani et al., 2011): Young's modulus and Poisson's ratio, $E_e=90$ GPa, $E_d=18$ GPa,