Research paper

Fracture susceptibility of worn teeth

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\textbf{ABSTRACT}

An experimental simulation study is made to determine the effects of occlusal wear on the capacity of teeth to resist fracture. Tests are carried out on model dome structures, using glass shells to represent enamel and epoxy filler to represent dentin. The top of the domes are ground and polished to produce flat surfaces of prescribed depths relative to shell thickness. The worn surfaces are then loaded axially with a hard sphere, or a hard or soft indenter, to represent extremes of food contacts. The loads required to drive longitudinal cracks around the side walls of the enamel to failure are measured as a function of relative wear depth. It is shown that increased wear can inhibit or enhance load-bearing capacity, depending on the nature of the contact. The results are discussed in the context of biological evolutionary pressures.

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\textbf{1. Introduction}

Teeth in humans and other animals are subject to deformation and fracture from normal biting function (Janis and Fortelius, 1988; Teaford, 1988; Maas and Dumont, 1999; Fortelius and Solounias, 2000; Lucas, 2004; Lucas et al., 2008; Constantino et al., 2010). Enamel is a uniquely hard tissue and provides external protection for a more compliant dentinal interior. Nevertheless, enamel can degrade from wear processes. The appearance of wear facets on natural teeth has been a topic of much interest in evolutionary biology circles (Welsch, 1967; Molnar, 1971, 1972; Grine, 1981; Teaford, 1988; Ungar, 1990; Fortelius and Solounias, 2000). In many mammals, prolonged wear from continual chewing on food matter can lead to pronounced enamel loss, in severe cases exposing the interior dentin and increasing the risk of disease (Janis and Fortelius, 1988; Dean et al., 1992; King et al., 2005; Sauther and Cuozzo, 2009; Elgart, 2010). In extreme cases teeth can wear to the gumline, at which point the animal can no longer consume its food and death ensues (Logan and Sanson, 2002). On the other hand, in grazing animals with columnar teeth wear can serve a useful function by shaping the tooth crown for more efficient food processing (Lucas et al., 2008). In some species, such as some rodents, teeth grow continuously to counter wear and chipping (Will et al., 1971). However, usually

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wear is an irreversible process. Physically, wear is produced by cumulative removal of enamel from microcontacts with hard silicate particulates, either errant dust particles in the atmosphere or phytoliths within the food matter itself (Baker et al., 1959; Molnar et al., 1983; Ungar et al., 1995; Piperno, 2006).

Recently, fracture has been identified as an important alternative mode of tooth degradation (Lucas et al., 2008; Chai et al., 2009a,b; Lawn and Lee, 2009; Lawn et al., 2009; Lee et al., 2009; Myoung et al., 2009; Lawn et al., 2010; Barani et al., 2011; Lee et al., in press). Tooth enamel is inherently brittle, and is subject to failure from longitudinal fractures at elevated loads. A simple schematic of tooth geometry and ensuing fracture modes is illustrated in Fig. 1. The model is representative of bunodont molar teeth in primates, in which the height \( H \) of the dome is just a little greater than the radius \( R \). The most deleterious form of fracture from axial contact loading at load \( P \) is from longitudinal cracking: radial–median (R) or margin (M) cracks. Secondary chipping or cone cracks (C) may develop.

The question then arises as to how wear and fracture processes may interact to influence tooth survival capacities. Specifically, in terms of Fig. 1, how may R and M fractures be influenced by the depth of wear \( w \) relative to the enamel thickness \( d \): \( w/d = 0 \) represents an unworn surface, \( w/d = 1 \) represents a surface with underlying dentin just exposed. A preliminary stress analysis using finite element modeling (Ford et al., 2009) suggests that reduced enamel thickness from wear may enhance some fracture modes but actually inhibit others, especially in the initiation phases. Confirmation of these predictions is a primary driving force for the present study. We conduct fracture tests on model glass shell structures containing polished flats of prescribed depths at the dome apex. The worn surfaces are loaded normally at the top surfaces with a hard sphere indenter, or hard or soft flat indenter, to represent extremes of food contacts. Tangential loading, while of critical importance in actual wear processes, is of secondary interest in our study of tensile fracture modes. The loads required to initiate and drive the cracks to failure are then measured as a function of wear depth, and the results considered in the context of biological selective pressures.

2. Experiments

Hemispherical shells of outer radius \( R = 6 \) mm and wall thickness \( d = 1.5 \) mm representative of bunodont tooth \((R/H = 1, \text{Fig. 1}) \) were blown from borosilicate glass plates. After cleaning in acetone, each shell was placed at the end of a plastic cylindrical mold of 12 mm diameter and 25 mm height and the mold then filled with epoxy adhesive resin [bisphenol-A-(epichlorohydrin) with amine hardener] which formed a strong bond to the glass. To avoid the introduction of shrinkage stresses during curing, the filling in the dome was applied in a minimum of 3 layers, each of which was allowed to cure for at least 24 h under the recommended curing conditions. The remaining support base of the mold was then filled and cured in a single casting. Top surfaces of the shells were then ground to prescribed depths \( w \) and polished to 1 \( \mu \)m finish. Specimens with wear depths \( w/d \) ranging from 0 to 1.5 were prepared.

Each specimen was mounted in a jig which was inserted into a mechanical testing machine, aligned axisymmetrically along the load axis. Indentation loads \( P \) were applied normally to the dome apex, in laboratory air at a crosshead speed 0.05 mm/min. One form of indenter was a hardened steel sphere of 12 mm diameter. Another indenter was the flat end of a cylinder of diameter 16 mm and length 20 mm, either of hardened steel (hard contact) or Teflon (soft contact). For the flat indenters, special care was taken with alignment to ensure that contact was distributed evenly across the worn surfaces. The metal indenters were used repeatedly, but Teflon indents were changed for each new test because of deformation of the polymer.

Each test was video recorded to enable post-test review of crack evolution, and thus to ascertain operable fracture modes. No evidence of debonding at the glass–epoxy interface was observed. Critical loads to drive cracks around the enamel side walls were recorded. A minimum of 20 specimens for each indenter type was used in the study.
Fig. 2 – Glass dome structures with epoxy filler, showing wear flats produced by grinding and polishing to relative depths \( w/d \) relative to shell thickness: (a) 0, (b) 0.6, (c) 1.5. A white circle is artificially superimposed onto the glass rim in (c) to highlight the interior epoxy filler. Width of base 12 mm.

Fig. 3 – Contact of glass dome with wear facet of depth \( w/d = 0.6 \) with hard sphere (HS) indenter. Showing video frame (a) immediately before and (b) immediately after longitudinal fracture. Note the appearance of precursor stable radial (R) cracks on side wall in (a). Cone (C) cracks are faintly visible on the wear flat.

3. Results

3.1. Fracture morphology

A sequence of epoxy-filled glass dome specimens with progressively severe surface wear states is shown in Fig. 2. The wear flat remains entirely within the glass for \( w/d \) values between 0 and 1; at \( w/d > 1 \) the epoxy is exposed within a glass rim. The fracture patterns from contact loading consisted primarily of R and M cracks, although some secondary cone cracking was also observed. Illustrative examples of the fracture patterns produced with each indenter type are given in Figs. 3–5 for specimens with intermediate wear facets at \( w/d = 0.6 \). The images in (a) and (b) in each of these figures are from consecutive video frames (<0.1 s interval), indicating configurations immediately before and after critical load. The appearance of full longitudinal fractures in the second of these frames highlights the abruptness of the crack instability. In most specimens multiple cracks formed en route to failure, much as reported in previous tests on unworn surfaces (Qasim et al., 2005). The nature of the longitudinal crack evolution depended on the indenter type. With hard spherical (HS) indenters (Fig. 3), most specimens revealed slowly developing R cracks. These cracks initiated at the inner surface of the flexing shell below the contact and then grew stably to the wear rim and just beyond with increasing load (Fig. 3(a)). With further slight increase in load the R crack propagated abruptly to the margin (Fig. 3(b)). This stable–unstable sequence was observed regardless of wear depth, and replicates that observed in earlier studies on similar, unworn surfaces (Qasim et al., 2005; Rudas et al., 2005). The remaining specimens displayed spontaneous fracture from the contact region without any visible precursor growth around the side wall. Critical loads to achieve final instability diminished with increasing wear depth. No M cracks were observed with concentrated indenters in our experiments, but incidental cone cracks were common, e.g. faintly visible beneath the indenting sphere surface (and in reflection on the indenting sphere surface) in Fig. 3.

Flat contacts produced analogous longitudinal crack patterns but with some important differences depending on whether the indenting material was hard (Fig. 4) or soft (Fig. 5). With hard flat (HF) indenters on unworn specimens \( (w/d = 0) \), R cracks again propagated stably onto the side walls prior to failure. However, on worn specimens failure occurred abruptly without any detectable initial stable growth stage. In these latter cases it was impossible to distinguish visually between failure from R and M cracks, although there are theoretical grounds for believing that M cracks become more prevalent at around \( w/d > 0.6 \) (see below). No secondary cone cracks were observed with HF indenters on worn surfaces, although occasional edge chipping and some spurious circumferential cracking was sometimes observed. With soft flat (SF) indenters, R and cone cracks were suppressed completely, at all wear states. In these specimens failure occurred spontaneously by abrupt propagation of M cracks from the base, as evidenced by a tendency for these cracks not to extend fully into the subsurface region below the worn surface.
3.2. Fracture loads

Critical fracture load data for worn glass/epoxy tooth models loaded with hard sphere (HS), hard flat (HF) or soft flat (SF) indenters are plotted in Fig. 6 as a function of occlusal wear. Each data point represents a different specimen, each symbol a different indenter type. The solid lines are trendlines. Notwithstanding considerable scatter in the data, the trendlines through each data set are distinctive, at least over a wear range $0 < w/d < 1$. The wear dependence in the region of lower critical loads, especially for hard sphere indenters, is brought out more clearly by plotting the ordinate in logarithmic coordinates. To recall, the predominant fracture mode for HS indenters is R cracking over the entire range of $w/d$; for SF indenters, M cracking over the entire range of $w/d$; for HF indenters, R cracking within $0 < w/d < 0.6$, with likely transition to M cracking around $w/d > 0.6$. Note that the curve corresponding to HF indenters merges asymptotically with that for SF indenters at large $w/d$, consistent with an R to M crack transition.

It is convenient to consider the critical load data in Fig. 6 for each indenter type relative to values for unworn surfaces ($w/d = 0$). Table 1 shows means and standard deviations for specimens in this pristine state. The critical loads for HS and HF indenters overlap within the standard deviation bounds. A student’s t-test on the data sets for these two hard indenter types show no significant difference ($p > 0.05$). On the other hand, the critical load for SF indenters is more than 3 times higher than for HF indenters. A t-test on the data sets for these two flat indenters confirms these differences to be significant ($p < 0.05$). These results highlight the susceptibility of rounded tooth structures to fracture from any type of hard contact.
4. Discussion

4.1. Fracture of worn surfaces

This study employs a simple experimental model, that of an epoxy-filled hemispherical glass dome, to investigate the fracture susceptibility of worn teeth (Fig. 2). Tooth wear is simulated by grinding and polishing flats on the dome surfaces, down through the glass (enamel) and, ultimately, into the underlying epoxy (dentin). In situ observations during axial loading of our polished-flat shell models with hard and soft indenters reveal much the same modes of fracture as those observed previously in unworn dome structures (Qasim et al., 2005, 2006a,b, 2007), namely radial–median (R) or margin (M) cracks extending longitudinally along the enamel walls (Figs. 3–5). In contacts with hard sphere (HS) indenters, R cracks tend to dominate the failure process, regardless of wear. With hard flats (HF), R cracks dominate at low w/d, but there is an apparent transition to dominant M cracks at larger w/d. With soft flats (SF), M cracks dominate. Analogous tests on dome structures with stiffer substrate fillers, including particulate-filled epoxy resins with modulus similar to tooth dentin, suggest that enamel/dentin modulus mismatch may influence this competition between R and M cracks (Kim et al., 2007). However, whether R or M cracks dominate is not of great consequence because the end result is the same: a longitudinal ribbon fracture extending between apex and base, signaling the onset of full-scale tooth failure (Lawn and Lee, 2009; Barani et al., 2011). In relatively unworn specimens loaded with HS indenters, there is evidence of an initial stage of stable growth prior to failure (Fig. 3). The main visual manifestation of an increasing wear facet, especially in the case of flat indenters (Figs. 4 and 5), is to diminish or obscure this initial stage, i.e. without stable growth onto the side walls—fracture then appears to grow abruptly from an ever-thinning glass layer within the scar rim or from the base.

Quantitatively, the influence of tooth wear is most compellingly apparent in the critical loads to drive R or M cracks to failure (Fig. 6). Starting with unworn dome surfaces, we find no discernible difference between critical loads for HS and HF contacts. This is physically understandable, since both hard indenter types make essentially similar concentrated contacts at the apex, favoring the initiation of R cracks from shell flexure (Deng et al., 2002; Qasim et al., 2005). An SF indenter, on the other hand, spreads the load across a larger contact area, diminishing the local stress intensity and redistributing the hoop stresses around the side walls, thereby making R crack initiation less likely (Qasim et al., 2007). A similar situation applies for HF indenters once wear flats develop on the apical surface, thereby spreading the load over a larger contact area and diminishing stress intensity at the apex. Soft contacts are especially effective in this regard, making it almost impossible to generate R cracks, thus favoring M cracks. Thus surface wear can actually provide some enhanced resistance to fracture, provided the contact is spread across the wear facet. On the other hand, concentrated HS contacts result in a notable reduction in sustainable load with progressive wear within 0 < w/d < 1, and are accordingly more dangerous. Interestingly, this latter loss of load-bearing capacity is reversed at extremes of wear, i.e. at w/d > 1, presumably because the axial HS contact is now borne by the exposed soft interior, thus once more diluting the local stress intensity.

Some secondary issues warrant consideration in the context of longitudinal fracture. One issue is our focus on crack propagation rather than initiation. The reasons for this focus are twofold: first, teeth are damage-tolerant structures, with a high density of preexisting microcrack-like flaws or defects within their natural microstructure (Chai et al., 2009a,b; Lawn and Lee, 2009; Lee et al., 2009; Myeong et al., 2009; Chai et al., 2010); second, longitudinal fractures tend to grow stably prior to ultimate propagation around the crack walls (Rudas et al., 2005; Lee et al., 2009; Barani et al., 2011). These features render the final failure state insensitive to the starting flaw condition. Another ancillary issue is that of off-axis loading. Such loading can shift the balance between R and M cracks, and can diminish corresponding critical loads (Qasim et al., 2006b). In the present case, a shift to off-axis loading of a severely worn surface with a concentrated load might be expected to cause spurious chipping at the glass rim encircling the wear scar. A hard flat indenter in imperfect alignment with the wear flat may produce a similar end result, with local chipping or circumferential cracking. However, we have been careful to exclude such specimens from our results.

4.2. Stress analysis

Explanation of the data trends with increasing wear depth in Fig. 6 requires some quantitative evaluation of the stress states along the crack trajectory. A first step to such an evaluation is a consideration of the stress distributions in the loaded, but uncracked, structure, using axisymmetric

| Table 1 – Critical loads with standard deviations for fracture in unworn glass/epoxy shell structures. |
|---|---|---|---|
| Indenter type | n | Fracture load (N) | Crack type |
| Hard sphere (HS) | 4 | 451 ± 135 | Radial (R) |
| Hard flat (HF) | 4 | 436 ± 80 | Radial (R) |
| Soft flat (SF) | 7 | 1461 ± 394 | Margin (M) |

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4.2. Stress analysis

Explanation of the data trends with increasing wear depth in Fig. 6 requires some quantitative evaluation of the stress states along the crack trajectory. A first step to such an evaluation is a consideration of the stress distributions in the loaded, but uncracked, structure, using axisymmetric
finite element modeling. For longitudinal fracture, we are primarily concerned with the tensile hoop stresses normal to the prospective crack plane within the shell. Such stresses have been previously evaluated by Ford et al. for the different indenter types as a function of wear depth, albeit for tooth enamel with a dentin interior (Ford et al., 2009). Fig. 7 presents analogous (normalized) stresses for our model glass dome system with epoxy interior, calculated from the same finite element configuration as before (Ford et al., 2009) but using the following input values: characteristic dimensions, $R = 6$ mm, $d = 1.5$ mm, $H = R = 6$ mm (bunodont human molars); glass shell, modulus 73 GPa and Poisson’s ratio 0.21; epoxy interior, modulus 3.4 GPa and Poisson’s ratio 0.35; HS indenter (radius $R = 6$ mm), modulus 220 GPa and Poisson’s ratio 0.30; HF indenter, modulus 220 GPa and Poisson’s ratio 0.30; SF indenter, modulus 0.5 GPa and Poisson’s ratio 0.35. While the modulus mismatch between glass and epoxy (73 GPa/3.4 GPa = 21) is markedly greater than for enamel and dentin (90 GPa/18 GPa = 5.0), with resultant increase in relative stresses portrayed in Fig. 7 by a factor of approximately 2, the broad trends with respect to relative depth $w/d$ observed in Fig. 7 are similar to those reported in the earlier work.

The plots in Fig. 7 represent two maxima in the shell hoop stresses $\sigma$. These maxima are located at the interface of the shell with the underlying core. The first maximum lies in the ‘apex’ region of the contact near field, where R cracks tend to initiate. Its location depends on the indentation conditions; it lies closer to the load axis for spherical indenters, but shifts outward toward the wear rim for flat indenters (Ford et al., 2009). The magnitudes of these stresses show strong sensitivity to indenter type and degree of wear. For unworn surfaces ($w/d = 0$), values for HS and HF indenters are indistinguishable, with those for SF indenters significantly lower. As wear progresses, the apex stresses for HS and HF indenters diverge substantially—those for spheres increasing and those for flats diminishing. This divergence correlates inversely with the critical load trends for HS and HF indenters in the region of small to moderate wear in Fig. 6, i.e. in the wear region where R cracks dominate. Physically, the divergence is explained by countervailing influences: in the case of spherical indenters, enhanced tensile stresses at the undersurface of an ever-thinning glass layer, plus reduced distances for R cracks to travel from the rim to the base; and in the case of flat indenters, a tendency for these same stresses to diminish in the region of a distributed contact and to transfer toward the glass rim.

The second maximum in $\sigma$ is located in the base region, where M cracks initiate. Base stresses are much less sensitive to indenter type across the entire wear range, since they are located in the contact far field. Consequently, apex and base maxima cross over as wear depth increases, depending on indenter type, in broad correlation with the experimentally observed transition from R to M cracking. With HF and SF indenters, base stresses dominate apex stresses beyond $w/d \approx 0.25$. In the region of severe wear, at $w/d > 1$, apex stresses are suppressed in all indenter configurations, including HS indenters where the contact is taken up by the compliant, exposed dentin, again leaving the base stresses dominant.

Such stress analyses from basic finite element modeling can be useful in explaining broad trends in fracture data, but they cannot provide a full quantitative account of the mechanics. Tensile stress maxima can tell where cracks are likely to initiate but they say little about the ensuing propagation stages to failure. For that, extended 3D finite element modeling (XFEM), with provision to evaluate stress intensity factors in stepwise fashion through the entire crack growth (Barani et al., 2011), is required. In effect, stress intensity factors involve an integration of stresses along the entire crack path (Lawn, 1993). Since contact-induced cracks tend to grow stably in their initial stages, the critical load for failure can be much higher than for initiation. This stability means that either R or M cracks may initiate first but subsequently be overtaken by competitors, even by a crack of a different mode (Barani et al., 2011). It also means that several cracks may initiate and extend along the shell walls simultaneously (Qasim et al., 2005; Rudas et al., 2005). However, XFEM computations are much more time consuming, and the simplistic stress analysis presented here suffices to account for the broader trends in the experimental data.

### 4.3. Strengths and limitations of glass-shell models

The use of glass-shell models in simulated occlusal loading has previously provided a great deal of insight into the basic fracture mechanisms in unworn teeth (Qasim et al., 2005, 2006b, 2007). Subsequent studies on extracted human teeth have confirmed the relevance of these mechanisms (Lawn and Lee, 2009; Lee et al., 2009). Critically, the use of glass shells permits subsurface fracture evolution to be observed directly, something impossible in actual semi-opaque tooth enamel. It is true that useful information on crack development can be gleaned by partially loading and then sectioning the tooth to observe any subsurface cracking (Chai et al., 2009a), but...
a complete description of crack formation and evolution – its stabilities and instabilities – can only be obtained by observing the structure in situ as the load is continually applied.

Another advantage of simple glass-shell models is the ability to control geometry in order to isolate the influence of various parameters on the critical conditions to fracture. In reality, the enamel thickness in molar teeth varies spatially, usually greater at the crown surface relative to that at the margin. The shape of crown is also more complex, exhibiting peaks and valleys around the cusps and geometrical variations at wear facets. Furthermore, these variations can differ widely between individual tooth specimens, even when taken from the same place in the jaw. It is impractical to isolate the effect of individual parameters under such circumstances. A simple experimental model allows us to observe these basic effects, understand the trends, and then apply this knowledge to explain and predict the behavior of more complex natural teeth (Whitton et al., 2008). Yet another issue is that of loading type, i.e. normal rather than tangential. In the interest of simplicity, our experiments have focused on normal axial loading. Off-axis loading usually has the effect of changing the orientation of the cracks and diminishing critical loads, but does not alter the basic mode of fracture (Qasim et al., 2006b; Whitton et al., 2008).

It is important to emphasize that our study does not set out to elucidate the actual processes that contribute to crown wear in tooth enamel, important as those processes are in the context of dietary analysis (Welsch, 1967; Molnar, 1971, 1972; Grine, 1981; Teaford, 1988; Ungar, 1990; Fortelius and Solounias, 2000). We have simply used polished flats to isolate the influence of wear on the fracture. Our interest in this specific study is in the post-hoc consequences of wear on the resistance of the structure to subsequent failure through the formation of radial–median (R) or margin (M) cracks under load. Wear analysis comprises an altogether separate field of endeavor, one that demands much further attention to tooth enamel morphology than we have given here. The influence of enamel morphology extends to fracture as well—it is pertinent that the direction of lowest fracture resistance, as determined by the orientation of mineralized rods, corresponds to the pathways followed by longitudinal R and M cracks, as observed in fracture experiments on extracted teeth (Chai et al., 2009a; Lawn and Lee, 2009; Myoung et al., 2009). It is in this context that the glass-shell models capture the essence of fracture behavior in actual tooth structures.

4.4. Biological implications

The contact loading of epoxy-filled glass dome models in this work captures the essential features of occlusal loading in rounded, bunodont molar teeth of humans and other mammals (Qasim et al., 2005; Lawn et al., 2010). Analogous contact tests on extracted human molars, mostly with flat indenters, do indeed show the same fracture modes as those observed in the model structures (Lucas et al., 2008; Chai et al., 2009b; Lawn and Lee, 2009; Lee et al., 2009; Lawn et al., 2010; Lee et al., in press). Minor variants are observed: in human molars, M cracks tend to be more prominent than R cracks, even for teeth in a relatively unworn state, presumably because of diminished enamel flexure on a stiffer dentin interior (Chai et al., 2009b; Barani et al., 2011). Regardless, longitudinal fracture remains the dominant failure mode.

The bunodont tooth form is also characteristic of fossil hominins, several other primates including all of the great apes, and many other mammals (Fisher, 1941; Swindler, 2002; Hillson, 2005; Lucas et al., 2008). Observations on molar teeth of primates and several mammals reveal similar fracture modes (Constantino et al., 2009; Lee et al., 2010; Constantino et al., 2011, in press), suggesting a certain commonality in fracture behavior in a wide range of animals. This commonality, in conjunction with detailed fracture mechanics analysis, has led to the suggestion that fracture ‘fingerprints’ on relatively unworn tooth specimens may be used to gain a measure of bite force for any given bunodont species (Lee et al., in press). These same fracture patterns may also be used to infer dietary propensities (Lucas et al., 2008). For instance, the appearance of incipient R cracks in Fig. 3, along with the HS data in Fig. 6, indicates a strongly enhanced susceptibility to fracture from hard foods with rounded surfaces, e.g. nuts and seeds. Interestingly, the manner in which fracture patterns may be influenced by diet-associated tooth wear in these species is a matter that has received little previous consideration. Given the ubiquity of wear in animal teeth, this is an area ripe for future study.

Almost any animal that has teeth exhibits wear to some degree during the course of its lifetime, and the underlying causes of that wear have been the subject of considerable discussion. With modern humans in developed nations, severe wear can arise from repetitive high-force tooth-on-tooth contact from inadvertent grinding or ‘bruxing’ (Carlsson et al., 2003). (Dentists counter this with the use of protective plastic ‘night guards’.) In most other mammals dental wear is attributable to food sources, generally from small, hard pervasive silica particles in vegetable matter (phytoliths) or exogenous grit in the soil, atmosphere or ocean (Teaford, 1988; Teaford and Ungar, 2000; Grine et al., 2010). Over time, human diet has trended toward highly processed foods, with little abrasion resistance to otherwise adverse tooth action (Lucas, 2004), although consumption of highly acidic soft drinks and regurgitation of stomach acids has led to enhanced erosion of the enamel (Millward et al., 1994; Bartlett et al., 1998). In more traditional human societies, as well as in prehistoric populations, enamel wear is considered a naturally occurring dietary phenomenon associated with a higher work rate necessary to break down tougher natural foods containing dietary abrasives (Molnar, 1972; Molnar et al., 1983; Dominy et al., 2008). The wear process is generally one of low-load (mN) microdeformation beneath small-scale (μm) contacts (He and Swain, 2007b,a,c, 2008), in which slippage along inter-prism boundaries within the near-surface enamel microstructure leads to progressive removal of surface material. Evaluation of the ensuing scratching and pitting patterns within the resulting facets is the work of microwear analysts. In fact, there is an entire field of study devoted to analysis of microwear markings on the teeth of both extant and extinct mammals, with an underlying aim of categorizing animals according to food properties (Walker et al., 1978; Grine, 1981; Janis and Fortelius, 1988; Teaford,
The effect of wear on tooth survival has strong implications for the health and lifespan of many animals. These implications extend beyond bunodonty to other tooth forms. In many animals that feed exclusively on plants, excessive wear can lead to total erosion of the teeth, thereby limiting the life expectancy of the animal. Less nutritious fibrous food sources of this type tend to require more chew cycles, with consequent enhancement of cumulative enamel degradation. Lemurs (King et al., 2005; Cuozzo and Sauther, 2006) and koalas (Logan and Sanson, 2002) with low ridged molars fall into this category. As humans force wildlife into more marginal habitats with lower quality food resources, such dental ‘senescence’ is likely to become ever more common. A large number of grazing animals have developed much longer, ‘hypsodont’ teeth, an elongate columnar form to counter such wear (Stirton, 1947; Williams and Kay, 2001; Mihlbachler and Solounias, 2006). In these latter animals wear is actually essential in order to produce sharp enamel ridges to aid in the breakdown of tough fibrous vegetation (Hillson, 2005). Longer teeth may also be selected to resist fracture, since any longitudinal cracks would then have further to travel along the enamel walls. On the other hand, continual wear may simultaneously render the tooth increasingly susceptible to failure from development and growth of R or M cracks. Such a condition might be exacerbated if a grazing animal were to incorporate occasional harder and larger food items into its diet. In elephants (Sikes, 1966), manatees (Domning and Hayek, 1984), and kangaroos (McArthur and Sanson, 1988) (and other ‘macropodid’ marsupials) (Lentle et al., 2003) the generation and anterior migration of new teeth (‘molar progression’) allows severely worn molars with diminished functionality to be pushed out of occlusion and replaced. Rodents (Williams and Kay, 2001), ‘lagomorphs’ (hares, rabbits, pikas) (Kraatz et al., 2010), and fossil species such as giant ground sloths and their armored relatives (‘glyptodonts’) (Bargo et al., 2006) feature ever-growing ‘hypsedont’ teeth to counter the effects of a tough, abrasive diet; in fact, in the absence of sufficient wear, these latter animals can suffer from a loss of jaw function and a variety of other deleterious conditions (Reiter, 2008).

5. Conclusions

We have conducted an experimental simulation study to determine the effects of progressive wear on the capacity of teeth to resist fracture. Tests have been carried out on model dome structures using transparent glass shells with polished flats to represent worn enamel and epoxy filler to represent dentin. Hard or soft indenting spheres or flat disks have been used to represent occlusal loading. The principal conclusions are:

(i) The evolution of fracture in specimens with worn flat surfaces under monotonic loading has been determined. The primary modes of fracture are longitudinal radial (R) and margin (M) cracking, although some secondary cone cracking has been noted.

(ii) Cracking tends to be ‘spontaneous’ in that, once initiated, the cracks propagate directly along the side walls to failure, especially in those specimens with greater wear.

(iii) The most deleterious contacts are those with hard sphere indenters. Critical loads for these indenters diminish as relative wear depth w/d increases, whereas critical loads for hard flat indenters increase. In these cases the principal mode of fracture is from R cracks. Corresponding loads for soft indenters are higher, independent of w/d, and occur principally from M cracks.

(iv) A finite element analysis of ‘hoop’ tensile stresses accounts for the data trends, explaining how locations of maximum stresses shift between apex and base with increasing w/d.

(v) Biological implications of the results have been outlined.

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