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Contact-Driven Crack Formation in Dental Ceramic Materials

Wei Li[1,a], Qing Li[1,2,b], Jeffery Loughran[2,c], Michael Swain[3,4,d], Ionut Ichim[4,e], Naoki Fujisawa[3,f]

[1]School of Aerospace and Mechanical Engineering, University of Sydney, NSW 2006, Australia

[2]School of Engineering, James Cook University, Townsville, QLD 4811, Australia

[3]Faculty of Dentistry, University of Sydney, NSW 2006, Australia

[4]Department of Oral Science, Faculty of Dentistry, University of Otago, New Zealand

[a]wei@aeromech.usyd.edu.au, [b]Qing.Li@aeromech.usyd.edu.au, [c]jeffrey.loughran@jcu.edu.au, [d]mswain@mail.usyd.edu.au, [e]ionut.ichim@stonebow.otago.ac.nz, [f]n.fujisawa@usyd.edu.au

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Abstract. Natural human tooth consists of multiple layered quasi-brittle biomaterials, which make dental restorations experience a complex stress state under masticatory contact loading. As such, many restorations are prone to failure and a constant effort is made to improve the mechanical characteristics of the restorative materials. Clinical observations have shown that improved strengths and fracture toughness in ceramic materials do not necessarily lead to an anticipated higher functional longevity of the restoration. While substantial experimental investigations have been carried out to identify the contact induced fracture in such multi-layer material systems, numerical modelling of this event was largely unexplored. This paper presents a new numerical method to account for micro-damage driven fracture in various multi-layered biomaterial structures. In this study, a Rankine constitutive model is adopted and the crack initiation and propagation are automatically implemented in an explicit finite element (FE) framework. The effects of indenter radius, surface curvature and thickness of layered biomaterials on the cracking patterns are investigated. The results show good agreement with the experimental studies in literature.

Introduction

Promoted by its excellent aesthetics and biocompatibility, ceramics are routinely and extensively used for dental restoration like inlays, crowns and bridges. However, the use of ceramics as restorative materials is limited mainly by their reduced loading capability due to inherent low fracture toughness. This shortcoming becomes particularly obvious when the ceramics are used in the layers, above the remaining enamel and/or dentine, and hence significantly affecting the functional longevity of dental restoration. More importantly due to complex mechanical interaction of these different materials an improvement of ceramic material properties may not necessarily guarantee a better restorative performance if it mismatched to other host dental materials [1]. For this reason, a new attention has been re-attracted to this topic in recent years [1-6].

A considerable experimental work was conducted by using an arrangement of glass (enamel) layer that was bonded with transparent epoxy (cement) to polycarbonate (dentine) [1], which allows one to observe the damage and fracture development across several layers of materials. Indeed, visible experiments reveal some important stages of the indentation test. The effects of indenter radius [1], surface curvature [2], coated thickness [3] have been explored. However, it is difficult to fully understand the damage and fracture mechanism without knowing the correlation of stress state with cracking. In this context, the existing numerical studies [1, 3] have been restricted to mainly a linear framework of stress analysis. It is therefore warranted to examine how the contact damage is accumulated and developed into fracture over the indentation. The paper aims at demonstrating the capability of a nonlinear explicit method in simulating crack nucleation and propagation so as to provide some new understanding how the geometrical parameters affect fracture patterns.

Methods and Materials

This paper presents a hybrid method of finite and discrete element to simulate the cumulative damage-driven crack nucleation and propagation in the layered material systems. Unlike the traditional numerical approaches, the new computational framework allows a smooth transition from continuum to discrete as well as corresponding topology update [7], which does not require placing any crack a priori. Instead, the crack nucleation and growth will be automatically determined by monitoring progressive damage of the material due to contact load applied.

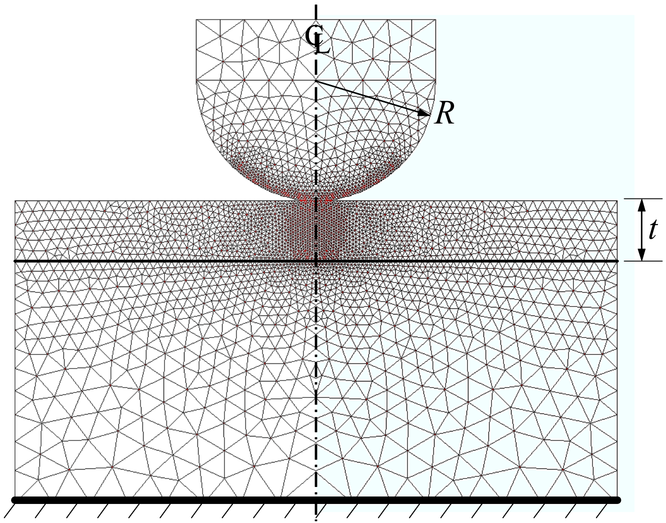


Fig. 1 FE model of bi-layered material system

Finite element model A parametric-based primary axisymmetric FE model is created as illustrated in Fig. 1. The indentation depth is considered as a kinematic driving force. In fact, half of the structure is modelled and analysed, but a whole domain is restored upon completion of analysis for clarification of observation in the figures below.

Material properties Fracture of brittle dental materials is assumed to relate to anisotropic phenomenon, where the micro-cracks develop towards the maximization of the subsequent energy release rate and the minimization of the strain energy density. The experiment demonstrates that the principal tensile stresses play a vital role to fracture these dental biomaterials. In this paper, a Rankine rotating crack constitutive model [7] is adopted for accommodating the failure of quasi-brittle materials. The indenter is modelled as the elastic material that has the same properties as the coated materials but without fracturing. The enamel or ceramics are considered for the coated materials, while the substrate is modelled as dentine. All the material properties are determined from [8].

Results and discussions

By using the hybrid continuum-to-discrete FE method, some layered dental material systems with different geometric parameters are investigated. These numerical models are used to benchmark the method presented and provide insightful understanding to the contact induced damage and fracture.

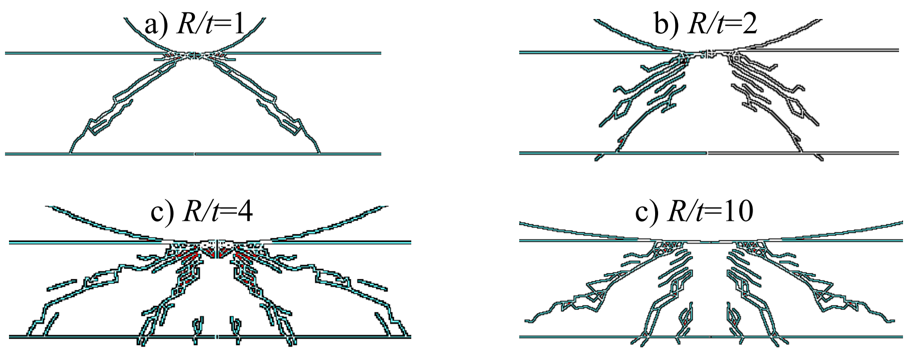
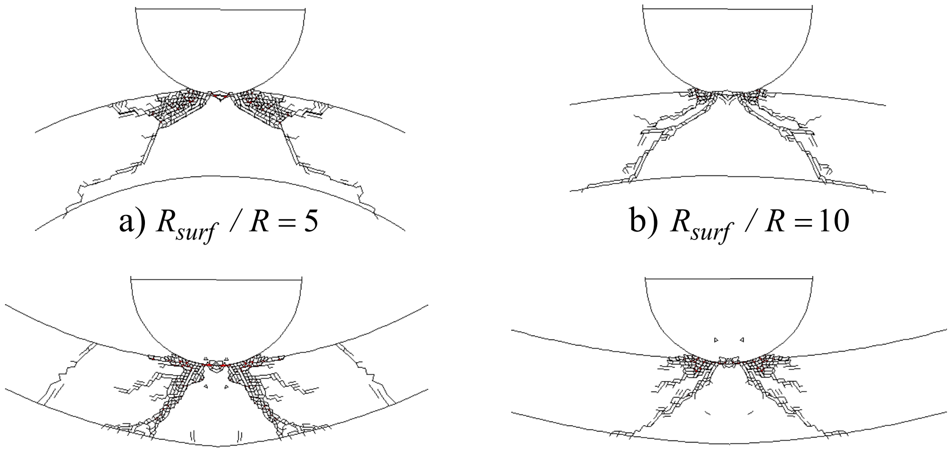


Fig. 2 Effect of indenter radius on the cone cracks

Effect of indenter radius on the cone cracks Experimental studies showed that the size of indenter is of significant influence in the contact induced damage [1]. More specifically, the indenter will determine the crack nucleation load and the ring crack radius. To explore such correlations, four different radii of the indenters are taken into account herein at a ratio to the coated layer thickness of 1, 2, 4 and 10 as shown in Fig. 2. Firstly, it is interesting note that all four scenarios clearly exhibit the "cone crack" patterns, which is in a very good agreement with the experimental observation [1-3]. Secondly, it is demonstrated that the greater the indenter radius, the larger the ring radius of the outer cone cracks, which again correlates to the experimental measurement well [1]. Thirdly, the small indenter radius leads to single cone cracks as shown in Figs. 2a) and b), while a large indenter yields to multiple cones as in Figs. 2c) and d). Multi-cone cracks attribute to a steeper gradient of stress field underneath the indenter.

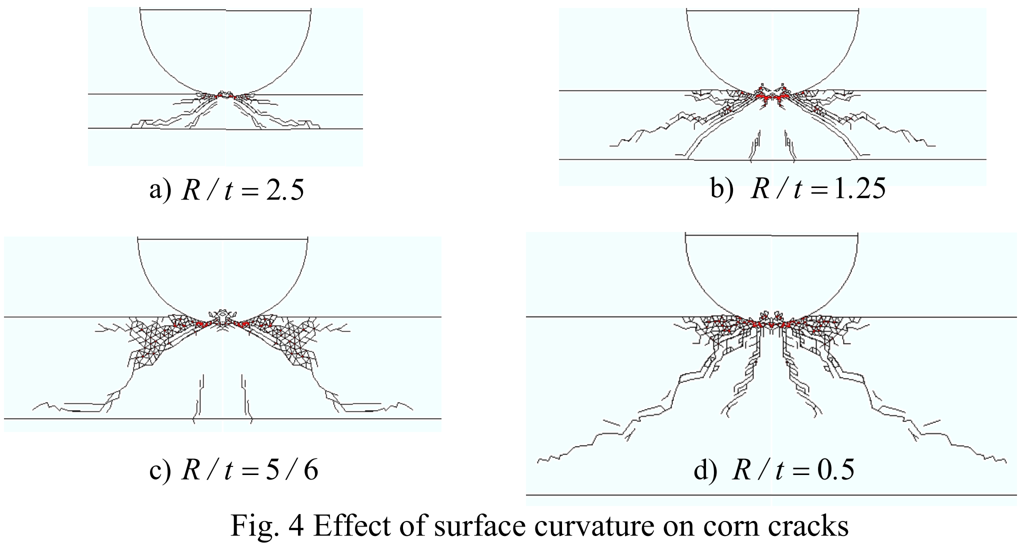


a) $R_{surf} / R = 5$ b) $R_{surf} / R = 10$

c) $R_{surf} / R = -5$ d) $R_{surf} / R = -10$

Fig. 3 Effect of surface curvature on corn cracks

Effect of surface curvature of layered materials Experimental investigations into the influence of surface curvature in the damage and fracture were conducted by Qasim et al [2,6]. In this study, two classes of curvatures, convex (Figs. 3a) and b)) and concave (Figs. 3c) and d)) surfaces, and each with two different radii, are taken into account. By comparing Figs. 3a) with b), and c) with d), it is observed that for both the convex and concave surfaces, the curvature has definite influence in the circumferential crack patterns. Such a phenomenon seems more evident in the cases of concave surfaces as in Figs. 3c) and d). In a larger curvature of concave surface, one can clearly observe the *inner* and *outer* cracking cones. Furthermore, comparing the convex with the concave surfaces having the same magnitudes of the curvature, it can see different fracture paths. In the convex surface, there is an apparent cracking path parallel to the convex interface of coated and substrate materials; the bigger the curvature, the longer such parallel cracking path, in Figs. 3a) and b).



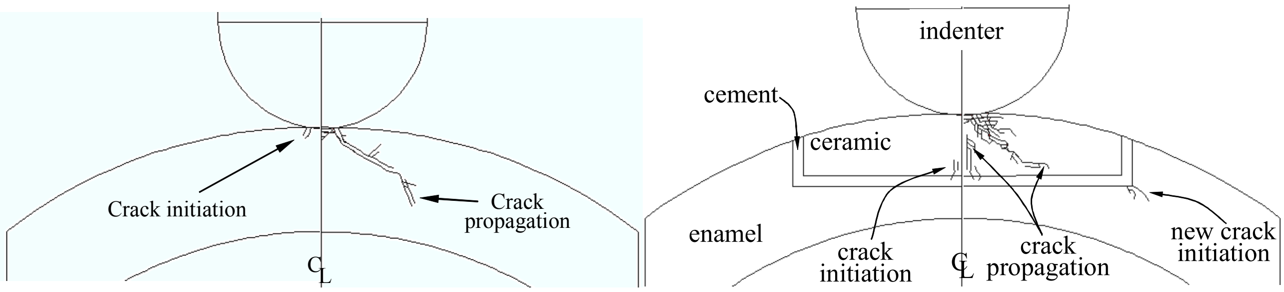
a) $R / t = 2.5$ b) $R / t = 1.25$

c) $R / t = 5/6$ d) $R / t = 0.5$

Fig. 4 Effect of surface curvature on corn cracks

Effect of thickness of the coated layer As a more brittle material, enamel has a much lower tensile strength ($\sigma_t = 30$MPa) and energy release rate (G_f=50N/m^2) compared with dentine ($\sigma_t = 105$MPa, G_f=100N/m^2 respectively) [3,8], which are responsible for that the fractures mainly occur in the enamel layer. The cracks rarely propagate across the interface of enamel and dentine in these numerical tests presented. It is therefore meaningful to explore the effect of thickness of enamel layer on crack patterns. Fig. 4 clearly exhibits that the cone cracks restrict their sizes by the thickness of the enamel layers. A thin layer of enamel yields shorter but multi-cones of cracks as in Figs. 4a) and b) in order to release a certain amount of strain energy. On contrast, a thick enamel layer leads to a longer fracture path while has less number of cracking cones, Figs. 4c) and d).

Contact-induced crack development in multi-material system It is meaningful to explore the crack nucleation and propagation in multi-layer dental materials. In the bi-material scenario, the crack initiates from the boundary of contact zone as shown in the left half of Fig. 6a) and propagates towards a cone crack as in the right half of Fig. 5a). In a ceramic restorative material system that involves ceramic, enamel, dentine and cement, however, the crack nucleates from the bottom of the ceramic filling and develops vertically before the cone crack forms as in the left of Fig. 5b), which well matches to the clinical observation. In addition, a dentine crack is observed in the corner of the restoration cavity in the right of Fig. 5b), which indicates that a sharp corner could damage to the healthy dentine host (substrate).



a) Crack develop in bi-material system b) Crack development in multi-material restoration

Fig. 5 Damage driven crack nucleation in bi-material model and multi-material restoration

Summary

Through benchmarking the numerical results obtained with the experiments, the study demonstrates the capability of simulating crack nucleation and propagation in the bi- or multi- dental biomaterial systems. The algorithm presented has shown the potentials to develop new insightful understanding in such complex stress states involving damage and cracking. The circumferential cone cracks are observed in most of these contact-induced fracture cases. The indenter radius, surface curvatures and layer thickness all contribute to the sizes and shapes of cracking cone. However, the axisymmetric model cannot predict the radial cracking unless 3D model is developed.

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