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The effect of adhesive failure and defects on the stress distribution in all-ceramic crowns

Yonggang Liu[a], Yuanzhi Xu[b], Bo Su[c], Dwayne Arola[d,e,f], Dongsheng Zhang[f,g,*]

[a] Shanghai Institute of Applied Mathematics and Mechanics, Shanghai, 200072, PR China
[b] The Tenth People's Hospital of Tongji University, Shanghai, 200072, PR China
[c] Bristol Dental School, University of Bristol, Bristol, BS1 2LY, UK
[d] Department of Materials Science and Engineering, University of Washington, Seattle, WA, 98195, USA
[e] Department of Restorative Dentistry, School of Dentistry, University of Washington, Seattle, WA, 98195, USA
[f] Department of Mechanics, Shanghai University, Shanghai, 200444, PR China
[g] Shanghai Key Laboratory of Mechanics in Energy Engineering, Shanghai, 200072, PR China

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ABSTRACT

Objectives: To explore the effect of adhesive failure and defects between the crown and cement on the stress distribution within all-ceramic crowns and the corresponding risk of failure.
Methods: An IPS e.max crown of lithium disilicate produced by CAD/CAM for a first mandibular molar was modeled using finite element analysis based on X-ray micro-CT scanned images. Predefined debonding states and interfacial defects between the crown and cement were simulated using the model. The first principal stress distribution of the crown and cement was analyzed under a vertical occlusal load of 600 N. A concept of failure risk was proposed to evaluate the crown.
Results: Stress concentrations in the crown were identified on the occlusal surface surrounding the region of loading, beneath the area of loading and at the margin of the interior surface. Stress concentrations in the cement were also evident at the boundary of the debonded areas. The lower surface of the crown is safe to sustain the 600 N vertical load, but the top surface of the cement would undergo cohesive failure. According to the evaluation of failure risk of the crown, the conditions of highest risk corresponded to the conditions with highest percentage of cement damage. The risk of failure is not only associated with debonding between the crown and cement, but also associated with its distribution.
Conclusions: Debonding related defects and cementing defects are more deleterious to the interfacial stress than debonding itself. The axial wall plays a critical role in maintaining the principal tensile stress of the crown at an acceptable level.

1. Introduction

All-ceramic crowns have quickly become commonplace in clinical practice due to a combination of desirable properties, such as aesthetics, biocompatibility and durability [1]. But due to their brittle behavior, all-ceramic crowns are more likely to fracture than their predecessors (e.g. metal or porcelain-fused-to-metal crowns) when they are used as dental prostheses [2,3]. In general, posterior all-ceramic restorations are subjected to much larger forces than those in the anterior region and this leads to a higher rate of failure [3].

Based on the higher relative risk of fracture of all-ceramic restorations, substantial efforts have been made to address this problem over the past two decades. The introduction of Computer Aided Design/Computer Aided Manufacturing (CAD/CAM) has helped to fabricate all-ceramic crowns with improved quality, minimizing drawbacks like voids and other volumetric defects. CAD/CAM also offers dentists the opportunity to prepare, design and fabricate ceramic restorations in a single appointment [4,5]. The inherent fracture strength of dental ceramic materials has been improved as well. For instance, the strength of zirconia, a core ceramic in double layered crown restorations, has reportedly exceeded 900 MPa [6–8].

Lithium disilicate glass-ceramic exhibits excellent shade varieties and translucency. Consequently, it has become an important veneer material for double-layer ceramic crowns [9,10]. The newly developed CAD/CAM lithium disilicates possess a flexural strength of approximately 360 MPa, which is sufficient to be used for posterior monolithic restorations [11,12]. Guess et al. [13] reported that IPS e.max CAD molar crowns were able to withstand masticatory forces. The reliability

* Corresponding author at: Department of Mechanics Shanghai University, 99 Shangda Road, Shanghai, 200444, PR China.
E-mail address: donzhang@staff.shu.edu.cn (D. Zhang).

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of monolithic lithium disilicate crowns has also been confirmed by fatigue tests [13,14]. Of course, a monolithic crown structure is advantageous as it eliminates the potential for failure associated with porcelain layering [15]. However, the load bearing capacity of ceramic crowns can be influenced by many factors, such as the tooth preparation, processes involved in manufacturing the restoration, and the luting process [16].

During the processes of manufacturing the restorations, several factors have been identified that may contribute to all-ceramic crown failures including [17]: (i) defects [18], (ii) residual stresses [19], and (iii) thermal residual stresses [20]. However, defects have been suggested to be the leading cause of failure [21]. Defects such as pores, inclusion and small cracks may cause stress concentration and become the site of subcritical crack growth [17]. Meanwhile, the fabrication of glass-ceramics may introduce processing defects, and crown failures are influenced by the size and location of such defects [22,23]. Thus, it is worthwhile to explore the relationship between defects and the risk of crown failures [17].

In regards to the luting process, most contemporary dental adhesives are able to achieve acceptable immediate bond strength. However, the bond reliability is dependent on both physical and chemical effects [24]. Physical bonding effects include, for example, micromechanical interlocking of the resin with the porcelain surface, which would be enhanced by pre-cementation surface roughening through hydrofluoric acid etching [25] or air abrasion [26]. Chemical bonding effects may include utilizing silane coatings (bifunctional coupling agents), which mediate covalent bonding between the inorganic porcelain and the organic resin [27]. Pre-cementation surface roughening and silane application can enhance porcelain-resin adhesion, the immediate bond quality between ceramic and cement and the fracture resistance of ceramic crowns [28]. However, the durability is a necessary consideration since bond degradation occurs via water sorption, hydrolysis of ester linkages of methacrylate resins, and activation of endogenous dentin matrix metalloproteinases [29].

The fracture resistance of all-ceramic restorations is maximized by improving the bond strength at the interface [30,31]. However, according to an evaluation of clinically failed and retrieved all-ceramic crowns, over 90% of glass-ceramic restoration failures are related to defects and stresses at the bonded interface [32]. Adhesive failure and interfacial defects are clinically relevant and potentially contributing factors to crown fractures. Cracks and debonding at the cement interfaces may be induced by poor luting processes or degradation of the adhesion [33]. Furthermore, the bond strength between the ceramic and cement is greatly influenced by cement type and cement aging [34]. Degradation of the bond strength reduces the load bearing capacity of full-coverage restorations [35–37]. Besides, weak bonds generated by compromised adaptation may cause gaps and microleakage [38]. Secondary caries in the mouth may also cause adhesive failure between the crown and cement [39], or between the dentin and cement [5].

Hernandez et al. [39] reported that approximately 65% of failures of ceramic blocks bonded using resin cement to a flat dentin substrate were found debonded between ceramic and cement under conditions of either water storage or mechanical loading. Interestingly, Nasrin et al. [15] found that lithium disilicate crowns subjected to fatigue loading were more likely to undergo early debonding at the wall area near the margin. Debonding is believed to originate at the margin of the shoulder due to the existence of marginal gaps [31,36]. These failures progress to the occlusal region with fatigue crack growth.

In general, simulating the process of adhesive failure that progresses over a long period of time is difficult to assess experimentally. The stress distribution within the cement that may contribute to interface failure is not available from experimental methods. Therefore, a numerical approach was adopted in this study to evaluate the stress distribution at the bonded interface between all-ceramic crown and tooth abutment with bonded interface debonding and defects. The aim of the present paper is to evaluate the risk of restored crown failure related to debonding and defects at the interface between the crown and cement. To understand the effect caused by interface debonding and its extent, a strategy of investigation was adopted that considered debonding percentages between crown and cement and different defect patterns. The null hypothesis of this investigation is that defects at the bonded interfaces do not increase the risk of all-ceramic crown failure.

2. Materials and Methods

2.1. Crown preparation

The monolithic lithium disilicate crown was selected as the ceramic restoration. The specific crown modeled in this investigation was based on IPS e.max CAD (Ivoclar Vivadent, Liechtenstein). A plaster mold and a concave silicon rubber mold were duplicated from the standard Asian first right mandibular molar (D50-500 A, Nissin Dental Products Co., Ltd.). The crown of the duplicate was trimmed so that the occlusal reduction was about 2 mm at the contact area, and with coronal length of 4 mm; the shoulder was prepared with 1 mm reduction on the lingual and buccal surfaces. Lithium disilicate crowns require a minimum occlusal layer thickness of 1.5 - 2 mm to resist failure by cyclic loading in the mouth [40–42]. The trimmed tooth was tapered at 8 degrees with a 1 mm shoulder of 90º. Then the trimmed plaster mold was used to duplicate the dental substrate with Z100™ (3 M ESPE, St. Paul, MI, USA). Instead of manufacturing the crown using IPS e.max CAD, the monolithic crown was prepared with a unique mixture of barium sulfate and denture base resin (Type II) (Shanghai Medical Instruments Co., Ltd., Shanghai, China) to develop high-contrast grayscale levels in X-ray radiation. The ratio of the two parts was 3:10 and the crown was built after the hardening process. The crown was carefully sanded and polished. The average thickness of the facet area of the crown was about 2 mm and the thickness gradually decreased to 1 mm at the shoulder.

2.2. Finite element modeling and simulation

The restored tooth was scanned with a GE micro-CT scanner with a voxel resolution of 20 μm. The sequential sliced images were imported into the 3D image conversion software, Simpleware (version 6.0, Simpleware Ltd., UK), in Dicom format, which converted the sliced images acquired from CT into a numerical 3D model. The software also provided means for smoothing the surface, assigning material properties and meshing. As shown in Fig. 1, the meshed model contained three components including the ceramic crown, cement layer and tooth substrate. Some important geometric dimensions are included in the figure for reference. The meshed model was imported into ABAQUS/CAE 6.10 software (Dassault Systemes Simulia Corp., Providence, RI, USA). Details of the final meshed models and material parameters are listed in Table 1. Note that the restoration was cemented to the dentin substrate using RelyX ARC (3 M-ESPE St. Paul, MN) in the simulation, which is common practice in China. In the finite element analysis (FEA), all of the materials were treated as linear-elastic, isotropic, and homogeneous [45]. According to the microstructure, dentin is basically anisotropic. However, since the purpose of this study is to analyze the stress distribution in the ceramic crown, the substrate dentin was treated as an isotropic continuum with linear elastic properties [46]. In addition, since the inhomogeneity of the tubule is several orders of magnitude smaller than the features of the crown preparation, the substrate dentine was also regarded as homogeneous and a continuum.

In order to evaluate the stress distribution within the monolithic restoration and account for evolution of debonding, seven finite element (FE) models were generated. Due to the differences in geometry, these models had a different number of total elements and nodes. A convergence analysis was conducted for each model to avoid quantitative differences in the stress values associated with meshing.

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