Contact fracture of full-ceramic crowns subjected to occlusal loads

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The mechanisms contributing to failure of full dental ceramic crowns under occlusal loads were studied using a unique optical approach. Model specimens comprising triple-layered crowns (veneer, core and substrate) were developed with both flat and curved occlusal surfaces and then subjected to simulated quasi-static occlusal loading using a spherical indenter. Deformation within the specimens during loading was analyzed by means of digital image correlation (DIC). Finite element models were also developed and used to examine the mechanics of contact. Results of the experiments with flat dental crowns indicated three typical modes of failure, i.e. cone cracks, plastic yielding and radial cracks. Fracture of the specimens with curved dental crowns was complicated by contributions from competing and multiple modes of failure. Both experimental and numerical results conclude that the dominant fracture mode in the full-ceramic crowns was radial cracking in the core beneath the contact area. However, displacement fields obtained using DIC showed that debonding developed near the shoulder of the crown, particularly during off-axis loading, and initiated under substantially lower occlusal loads than those required for crack initiation.

1. Introduction

Research on ceramic crowns over the past two decades has focused primarily on net-shape processing (Tabellion, 2006; Zhu et al., 2004), machining (Bindl and Mörmann, 2005; Sulaiman et al., 1997), improving the structural properties of full-ceramic systems (Kelly, 1997; Lawn et al., 2004; Quinn et al., 2005) and analyzing clinical failures (Kelly, 1999; Scherrer et al., 2006; Taskonak and Sertgoz, 2006). In practice, full-ceramic crowns are usually fabricated into layer structures with esthetic, but comparatively weak, veneer porcelains on stiff and strong ceramic support cores. The failure modes of these layered structures have been studied by means of Hertzian contact testing (Rhee et al., 2001), and under these laboratory protocols there are three primary damage modes including surface cone cracks, a quasi-plastic yield zone at the top surface (porcelain) and radial cracks at ceramic bottom surfaces (core). It should be understood that only radial cracking without Hertzian cone damage is reported from clinically failed crowns. In evaluations of layered dental ceramics, the critical contact loads have been evaluated in terms of fundamental materials properties and specific geometric variables (Chai and Lawn, 2004; Deng et al., 2002a, b; Lawn et al., 2004; Thompson and Rekow, 2004). Due to the complex geometry of the tooth crown and nature of contact under masticatory conditions, evaluations on the fracture of ceramic crowns have often been simplified as a flat layered structure. Though the influence of surface curvature has been considered (Qasim et al., 2005, 2006), the modes of fracture occurring in actual dental crowns have not been examined in detail due to the difficulties encountered in visualizing the inception and propagation of damage in opaque materials (Rekow and Thompson, 2007). Digital image correlation (DIC) has found a tremendous number of applications in quantifying displacement and strain distributions in many engineering environments. As it uses very simple optical equipment and acquires deformation in two orthogonal directions at one time, it becomes a method of choice in experimental mechanics (e.g. Li et al., 2006; Tong, 2005; Zhang and Arola, 2004).

In this study, two types of sectioned tooth-like ceramic crowns were prepared and examined under contact conditions using a combination of experimental and numerical methods. DIC was adopted to identify the onset of cracking in the crown structure and followed by a 3D FEA analysis. The objective of the study was to evaluate application of a unique optical approach for evaluating the mechanisms and mechanics of fracture in opaque ceramic systems. Results of the investigation are presented and discussed in light of the existing knowledge on model layer systems.
2. Materials and methods

The experimental methods comprised developing specimens with sectioned dental crowns and the application of an optical approach for characterizing crack initiation and extension. In addition, finite element modeling was applied to evaluate the mechanics associated with contact loading and the potential modes of failure.

2.1. Specimen preparation

The dental ceramic crowns involved in this paper comprised IPS Empress II (Ivoclar Vivadent, Liechtenstein). In order to make comparison with the well-established theory of ceramic fracture mechanism, two types of crowns, i.e. with flat (Type A) and curved (Type B) surfaces, were prepared. Type A crown comprised a flat triple-layered structure comprising a veneer, core and tooth-like substrate. As shown in Fig. 1(a), the core was 0.8 mm and the porcelain was 1.2 mm, to meet a total thickness of 2 mm above the substrate. Type B crown was made according to the geometry and size of a standard first right mandibular molar (DSO-500A, Nissin Dental Products Co., Ltd.) and involved a series of detailed procedures. First, a plaster mold was duplicated from the standard Asian first right mandible molar. A slice with a thickness of 2 mm was sectioned along the facial-lingual direction. The crown of the sectioned tooth slice was trimmed so that the occlusal reduction was about 2 mm at the contact area with a coronal length of 4 mm; the shoulder was prepared with 1 mm reduction in lingual and buccal surfaces. The trimmed tooth was tapered at 8° with a chamfer of 135°. A wax core mold was made on the top of the trimmed tooth with a thickness of 0.8 mm. Meanwhile, the trimmed plaster mold was used to duplicate the dental substrate with 3M™ ESPE™ Z100™ Restorative polymer (3M ESPE, USA). Following standard procedures, the IPS Empress II core was fabricated according to the geometry of the wax mold in the dental laboratory. The Empress porcelain veneer was stacked on the core in a Programat P100 furnace. The stacked porcelain surface was then ground carefully and sanded using 400 and 800 mesh SiC paper. The sectioned crown was placed back into the furnace to remove possible microcracks that might be introduced during sanding, and then glued onto the dental polymeric substrate with Ivoclar Variolink II cement (Ivoclar Vivadent, Liechtenstein) (Fig. 1(b)). Six specimens were prepared for each of the two crown types (flat and curved).

2.2. Equipment and procedures

The specimens were subjected to monotonic occlusal-like contact at the center of the porcelain surface through a tungsten carbide sphere with a diameter of 6 mm. Static loading was performed vertically using a specially designed fixture that rigidly supported the root of the sectioned specimens. Though the vertical load was generally aligned with the tooth’s axis, a small degree of misalignment was evident in some specimens with a curved crown; the maximum misalignment was approximately 10°. In order to document the crack initiation and propagation process, a stably increasing loading protocol was expected. The compressive load was applied using a Zwick B22/TS15 universal test machine at a rate of 0.005 mm/min (displacement control mode). The corresponding load increase rate is about 1.9 N/s. A video camera (Model JAI CV-A1) was placed normal to the sectioned specimen to acquire images necessary for performing image correlation. According to the image resolution (1376 × 1035 pixels), one pixel length represented approximately 10 μm. Sequential images were acquired at a constant frequency of 0.5 Hz during loading.

2.3. Digital image correlation

In the present study, DIC was employed to quantify the full-field displacement distribution within the crown, identify the location of crack initiation and evaluate the nature of crack extension. To facilitate the application of DIC, the normal surface of the sectioned dental crown was prepared with a thin coating (approx. 5 μm) of splashed fine black speckles, where the speckles were arbitrarily distributed by means of a spraying technique (Zhang et al., 2002, 2004). Overall, speckle particles had an average diameter around 100 μm or less.

The full-field displacement distribution within the crown was examined as a function of loading. Displacements were quantified in the direction of loading (vertical direction, “v-field”) and transverse to that direction (horizontal direction, “u-field”). As DIC provides a displacement resolution of 0.05 pixels or approximately 0.5 μm, it provides an accurate detector to study how the crack initiated and propagated. Since the displacement distribution is not continuous across the edge of the crack, a crack can be identified by an apparent discontinuity in a grayscale map, which presents the displacement magnitude field.

2.4. Numerical methods

Finite element models were developed for full-ceramic crown systems. A dummy IPS Empress II full-ceramic crown restoration of the mandible right first molar was prepared according to the standard dental process. It was scanned with a GE micro-CT scanner and the 3D numerical model with 800,491 elements and 1,128,058 nodes were generated with the help of Simpleware1 (Magne, 2007). Table 2 shows the material properties (Chung and Yap, 2005; Imanishi et al., 2003) used in numerical analysis. The bottom of the dental substrate was constrained with displacement in all directions equal to zero. Similar to the experimental, 600 N occlusal loads were applied on the wear facets (De Jager et al., 2005; Imanishi et al., 2003). To simulate the experimental loading conditions, two contact areas were chosen near the central fossa along the facial-lingual direction. Loads were applied in their normal directions, respectively. Two cases were considered: the resultant load is applied along the tooth axis and the resultant load had an angle about 10° off the tooth axis.

3. Results

The loads responsible for different modes of crack initiation for both crown types are listed in Table 1. In most cases, the load at rupture (complete failure) was approximately 100 N larger than the load resulting in crack initiation. Rupture was identified either by visual evidence of catastrophic failure or by a decrease in the axial load response thereof. On examination of the specimens with flat crowns, the yielding zone expanded from the contact point to a peripheral area with increasing load. Cone crack appeared at the boundary between the yielding and elastic zones. Propagation of the cone crack was generally arrested at approximately 2/3 of the veneer thickness. Rupture occurred at a larger occlusal load due to fracture in the core layer (radial crack) or extension of the cone crack and debonding at the interface on the substrate (Fig. 2(a) and (b); Table 2).

1 http://www.simpleware.com/.
The curved crown specimens were loaded according to natural contact that develops during mastication and in a consistent manner to the specimens with a flat crown. Due to the radius of the contact sphere, the actual contact positions were located adjacent to the central fossa (Fig. 3(a)). Analogous to the failure of flat crowns, cone cracks initiated first and were generally audible when crack length increased. However, they were more evident from the displacement distribution obtained using DIC at the onset of crack generation. An example of the displacement field in the horizontal and vertical directions for a curved crown specimen is shown in Fig. 3(b) and (c), respectively. The cone cracks are

Table 1

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Flat crown</th>
<th>Specimen</th>
<th>Curved crown</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>Crack Initiation (N)</td>
<td>690</td>
<td>528</td>
</tr>
<tr>
<td>2</td>
<td>Fracture Mode</td>
<td>Cone cracking Radial cracking</td>
<td>Cone and radial cracking</td>
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<tr>
<td>3</td>
<td>Fracture Load (N)</td>
<td>658</td>
<td>606</td>
</tr>
<tr>
<td>4</td>
<td>Fracture Mode</td>
<td>Cone cracking</td>
<td>Cone cracking</td>
</tr>
<tr>
<td>5</td>
<td>Fracture Load (N)</td>
<td>668</td>
<td>N/A</td>
</tr>
<tr>
<td>6</td>
<td>Fracture Mode</td>
<td>Cone cracking</td>
<td>Debonding and radial cracking</td>
</tr>
</tbody>
</table>

Table 2

<table>
<thead>
<tr>
<th>Materials</th>
<th>Properties</th>
</tr>
</thead>
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<tr>
<td></td>
<td>Young’s modulus (MPa)</td>
</tr>
<tr>
<td>IPS-Empress Veneer</td>
<td>6.72 × 10^4</td>
</tr>
<tr>
<td>IPS-Empress II core</td>
<td>1.02 × 10^5</td>
</tr>
<tr>
<td>3M ESPE Z100 polymer</td>
<td>1.48 × 10^4</td>
</tr>
<tr>
<td>Dentin</td>
<td>1.86 × 10^4</td>
</tr>
</tbody>
</table>

Fig. 2. The propagation of cracks in the flat layered crowns under occlusal loading. Black arrows indicate cone cracks and white arrows indicate radial cracks. The yielding zone is highlighted using patterned arrows. (a) Yielding zone and cone crack developed with the increase of occlusal load. (b) Rupture due to either radial cracking or extension of cone crack to interface.
highlighted with black arrows. The cracks are distinctly evident in the grayscale distribution due to the discontinuity in displacement arising at the crack boundary. The load magnitudes responsible for initiation of cone, radial and debonding cracks identified using DIC are listed in Table 1. With additional increase in load beyond crack initiation, radial cracks developed and caused rupture (Fig. 3(c)). Due to the curvature of the occlusal surface, debonding occurred at the adhesive interface near the crown’s shoulder in three out of six specimens, particularly in specimens with a larger degree of misalignment. Debonding was identified from the displacement discontinuity at the shoulder using DIC (Fig. 4) and the corresponding loads are listed in Table 1. Note that specimen 6 was subjected to the largest degree of off-axis loading and underwent debonding failure at a substantially lower load (168 N) than that required to initiate a cone crack. The rest of the specimens experienced similar crack initiation and propagation processes, and the average crack initiation and fracture load are 606±101 and 741±98 N, respectively. It is also evident that debonding occurs at the crack initiation stage with the curved crown specimens.

The 3D model of the full-ceramic crown restoration generated with Simpleware is shown in Fig. 5(a). As mentioned above, when loads were applied near the central fossa along the facial–lingual direction, the first principal stress distributions in this section are shown in Fig. 5(b) and (c). In Fig. 5(b), the applied resultant load was vertical and consistent with the tooth axis, while in Fig. 5(c) the resultant load had an angle of 10° inclined with the vertical direction. Near the contact areas in these two cases, the maximum flexural (tensile) stress was developed in the core layer as a result of bending deformation normally beneath the contact zone. The increasing flexural stress exceeded the strength of the core ceramic and enabled rupture of the crown. The maximum compressive stress was found just beneath contact areas in the veneer layer, as expected. Also, tensile stresses were developed adjacent to the contact areas, which gave rise to the initiation of cone cracks as identified in the experimental evaluation. Interestingly, at the shoulder, where the crown was bonded to the tooth substrate, tensile stresses were found with orientation perpendicular to the interface. If the resultant load was not aligned with the tooth’s axis (Fig. 5(c)), larger tensile stress could be resulted in those areas. Numerical results for the location of maximum principal stress (Fig. 5(c)) are in agreement with the characteristics of debonding failure observed in experiments (Fig. 4).

4. Discussion

At present, there is no other experimental approach that is capable of providing the measurement resolution of displacements and initiation of failure in opaque systems. In the present study, a special process was adopted to form sections of dental
crowns with clinically relevant size, geometry and materials. Using DIC, the full-field deformation in all three layers (i.e. veneer, core and substrate) was evaluated as a result of simulated occlusal loading. Considering the size of the specimen, resolution of the digital images and the precision of DIC, the displacement resolution was 0.5 μm. Through the presence of discontinuities in the processed displacement fields, it was possible to identify the initiation of cracks and interfacial debonding. According to the results from 3D finite element analysis, the crack initiation and fracture modes can be well explained by stress distribution at the section across the central fossa along the facial–lingual direction. Thus, the sectioned crown and complimentary optical analysis offered a direct and precise means for identifying the mode of failure and critical occlusal load. The new experimental approach could serve as a valuable supplement to the constitutive models proposed for describing failures in dental ceramics that have been developed using model transparent materials (Chai and Lawn, 2004; Deng et al., 2002a, b; Lawn et al., 2004; Thompson and Rekow, 2004). In particular, the approach can be applied to validate design principles adopted for dental crowns manufactured from newly developed and/or existing clinically relevant ceramics.

The core and veneer thicknesses in the model crowns were 0.8 and 1.2 mm, respectively. This layout is most common for full-ceramic crown designs prepared within clinics in China. When the flat triple-layered crowns were subjected to occlusal loads applied by a 6-mm-diameter tungsten carbide ball, cone cracking and a yielding zone were detected at the early stage of crown failure. The dominant modes of fracture (i.e. rupture) included radial cracking originating from tension at the bottom of the core layer beneath the contact load, or extension of cone cracks that caused debonding at the interface of the core and the substrate (Fig. 3(b)). Despite variations in the mode (or modes) of fracture, the critical loads recorded for the specimens with a flat crown (Table 1) were relatively consistent, as evidenced from the coefficient of variation (COV = 0.11 for both crack initiation and fracture). These results support those reported by Lawn et al. (2004) and others (Chai and Lawn, 2004; Thompson and Rekow, 2004) for Empress II glass-ceramics concerning the optimal design thickness of the core and veneer and potential modes of failure, i.e. cone cracks developing in the veneer were arrested at the veneer/core interfacial region. Rupture occurred due to the development and propagation of radial cracks, which are consistent with the results of previous investigators (Deng et al., 2002a, b). According to the numerical simulations (Fig. 5(a)), occlusal loading resulted in maximum principal stresses distributed at the bottom of the core, and is responsible for the development of radial cracks.

In specimens with a curved crown, contact developed adjacent to the central fossa with the opposing cusps. The maximum flexural tensile stresses developed within the core at locations beneath the contact normal as indicated in Fig. 5(b). Table 1 shows that in contrast to results for the flat layered crowns, there are larger variations in the critical load for crack initiation and fracture in the curved layered crowns (Table 1; COV = 0.17 and 0.13, respectively). While the average loads to crack initiation for the two crown systems were not significantly different, the large variability could enable premature failures and/or unexpected failures in the actual crowns. Also, all of the specimens with a curved crown fractured (ruptured) due to radial cracking; propagation of cone cracks was not a key factor.

While the maximum bite force for adults may reach 700–800 N (Craig, 1997; Nishigawa et al., 2001), the common occlusal load in oral conditions ranges below 400 N, ceramic crowns rarely undergo rupture due to fracture strength of Empress II as a result of routine function in the initial service time. However, rupture could happen due to the accumulation of fatigue stress (El-Mowafy and Brochu, 2002). This agrees with many clinical assessments of failure in full crowns comprising IPS Empress ceramics (Chen et al., 2004; Gemalmaz and Ergin, 2002). Although
IPS Empress II is lithium-disilicate-reinforced ceramics, which has better mechanical performance than that of leucite-reinforced ceramics, it is expected that it would have the same trend of failure modes due to the nature of ceramics. Although the ultimate fracture was due to the radial crack, it is obvious to observe debonding caused by tensile stress occurring at the shoulder either in experiments (Table 1) or in numerical simulations (Fig. 5). As oral function of the posterior molar comprises of biting and grinding, the resultant contact force is not directly aligned with the tooth’s axis. Misaligned occlusal loading simulated using the finite element model (Fig. 5(c)) showed that the maximum tensile stress still develops in the ceramic core beneath the contact normal, but with the addition of considerable tensile stress at the shoulder normal to the interface. Hence, the nature of contact that develops during normal oral function on curves with curved surfaces can foster debonding at the shoulder of the crown at a relatively low occlusal load (Fig. 4). Microtensile bonding test had proved that the use of different types of luting agents can cause a large change of bonding strength between IPS Empress II and dentin (Escribano and de la Macorra, 2006). While the crown itself was not cracked at the load responsible for debonding, leakage and bacterial invasion can become a greater concern. Previous methods of examining full-ceramic crown failures in model transparent systems could miss to capture this mode of failure. Further studies aimed at examining chamfer preparations and adhesives should be conducted using the proposed experimental approach in order to understand contributors to debonding and to identify potential methods for reducing their contribution to clinical failures.

Conflicts of interest

The authors, Dongsheng Zhang, Chenglin Lu, Xiuyin Zhang, Shuangshuang Mao and Dwayne Arola, declare that they have no proprietary, financial, professional or other personal interest of any nature or any kind in any product, service and/or company that could be constructed as influencing the position presented in, or the review of, the manuscript entitled, “Contact Fracture of Full-ceramic Crowns Subjected to Occlusal Loads”.

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