The role of skirt geometry of dental crowns on the mechanics of failure: Experimental and numerical study

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Abstract

Dental crown structures were modelled using a curved bi-layer system consisting of a brittle glass coating on a compliant polymeric substrate, to illustrate the role of skirt geometry on the mechanics of failure evolution. The geometries of the samples were varied by tapering the skirts of the glass shells in different lengths and thicknesses. The failure of these samples was investigated under single-cycle axial loading tests using an indenter of low elastic modulus. The onset of fracture was observed in situ using a video camera. A relationship between the height and thickness of the taper and the critical load required for a crack to appear in the sample was observed. Margin cracks were observed to propagate from flaws near the margins. Experimental trends suggested that critical loads increased with increasing taper thickness, and decreased with increasing taper length. Finite element modelling was also used to evaluate the stress distribution in the glass coating. Peak maximum principal stresses at the margins decreased with increasing taper thickness, and increased with increasing taper length, consistent with the experimentally determined critical loads. It is concluded that long, narrow tapers should be avoided in order to maximise the load bearing capacity of dental crowns.

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1. Introduction

Layered structures featuring ceramic materials are finding increasingly common usage in a wide range of engineering applications including biomechanical replacements such as dental crowns, hip and knee prostheses, heart valves and bone implants [1–3]. The combination of a hard, brittle outer layer and a compliant, tough inner layer offers high wear resistance and damage tolerance, factors that are crucial to the lifetime of such structures. Generally, these structures include more than one material type – ceramic, metal, and polymer – in layered or composite configurations. In biomechanical prostheses ceramics are replacing metals as a material of choice, where biocompatibility, chemical durability, and aesthetics are critical issues [4].

A simple bi-layer system model of a dental crown, utilising a hemispherical glass shell as the brittle layer and epoxy resin as the compliant substrate, can be tested to determine the “critical load” necessary to initiate the first crack during compression testing. Glass is a suitable brittle test material as it has an elastic modulus of approximately 73 GPa, similar to that of tooth enamel or dental porcelain commonly used in crowns [5]. Epoxy resin is an inexpensive and easily prepared polymeric substrate. This design mimics the essential structure of monolithic all-ceramic dental crowns on natural tooth dentine. Previous studies have focused on failures of such bi-layer systems under indentation with “hard” indenters with a large elastic modulus to simulate occlusal contact. The crack modes observed in such experiments did not explain the “semi-lunar” failures of dental crowns observed in clinical cases, where cracks initiate at the base of the crown (or margin), and eventually join causing material loss. Examples of a “semi-lunar” failure are shown in Fig. 1. For this reason, a study by Qasim et al. [6] shifted toward the use of “soft” indenters with a lower elastic modulus. The soft indenters deformed under loading which resulted in a distributed...
load over the samples, simulating loading of a crown during mastication of soft food. The distributed load creates a large compression zone directly beneath the indenter, eliminating the tensile stresses in that region that would otherwise lead to radial cracking. The location of the peak principal stresses instead shifted to occur near the margins. The study, conducted with a balsa wood indenter and a hemispherical bilayer glass–epoxy system, found that the soft indenter caused the propagation of margin fractures from large pre-existing cracks. A comparison of hard and soft indenters in another study by Qasim et al. [7] concluded that softer indenters are more likely to generate margin damage than hard indenters.

The purpose of the current study was twofold. Firstly, the geometry of the skirt (side walls) of the glass specimens was tapered to see what effect the length and width of the taper had on the critical loads to initiate fracture. Secondly, the effect of using a soft polytetrafluoroethylene (Teflon) indenter on the incidence of margin cracks was tested. Un-tapered samples of similar heights to the tapered samples were tested for comparison. Experimental results were analysed using finite element modelling (FEM) of the stress states at the brittle layer under-surfaces, and compared with experimental results of the system under consideration here.

2. Experimental procedure

2.1. Specimen fabrication

A schematic of the hemispherical samples tested is provided in Fig. 2. The inner radius \( r_s \) of the samples was 6 mm and the thickness of glass \( d \) was 1 mm. The length of the specimen that extended below the hemisphere, the skirt length \( L_S \), was held constant at 4.0 mm, while the length of taper \( L_T \) varied from 0.0 to 4.0 mm. The width of the taper \( t \) varied from approximately 0.4 to 0.7 mm. For the un-tapered specimens, \( t = d \). Curved glass/epoxy bi-layers, in the configuration of Fig. 2, were fabricated for indentation testing. Properties of the relevant materials are shown in Table 1. First a test tube was created using 14 mm outside diameter, 1 mm thick glass tubing (Borosilicate glass, Schott Duran, Germany). The tapered specimens were formed by heating the body of test tube below the rounded end and drawing it out to form the tapered margin. Samples with taper lengths \( L_T \) between 1 and 4 mm were produced in this manner. All samples were heat treated to 565 °C for 30 min then cooled slowly to remove residual stresses created by the forming process. Grinding the base of the tapered samples using P120 grade silicon carbide (SiC) grinding paper was required to
remove the glass bead that formed at the margin during the drawing process. Grinding of the base of all specimens using P120 grade SiC paper was also required to obtain the correct skirt length \( L_s \). Although grinding could induce some damage at the margins, care was taken and no visible damage was observed.

The inner surface of each glass shell was sandblasted with 50 \( \mu \)m sand particles using a dental sandblasting machine (PG4000 Harmish and Reith, Czech Republic). This procedure is conducted to reduce the strength of the glass close to that of porcelain, and also to facilitate bonding of the epoxy resin to the glass. The sandblasting also favours the formation of radial cracks and provides a more uniform flaw distribution [4,6].

The glass hemispheres were inverted in a mould and epoxy resin (R2512, ATL Composites, Australia) was added in thin layers <5 mm, according to the manufacturer’s specifications. Each successive layer was allowed to cure under the action of a medium hardener for 24 h before adding the next, to minimize the effect of shrinkage stresses on the glass. A further \( h = 6 \) mm of epoxy resin extending further than the margins (extremities) of the glass shells was added in one setting. This provided support for the samples during testing, after grinding the bottom surface of the extended support layer until parallel to the base of the glass hemisphere.

\[ T \]

Table 1

<table>
<thead>
<tr>
<th>Material</th>
<th>Young’s modulus, ( E ) (GPa)</th>
<th>Poisson’s ratio, ( \nu )</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indenter</td>
<td>Teflon</td>
<td>0.48</td>
<td>Elastoplastic</td>
</tr>
<tr>
<td>Coating</td>
<td>Glass</td>
<td>73.0</td>
<td>Elastic</td>
</tr>
<tr>
<td>Substrate</td>
<td>Epoxy resin</td>
<td>3.4</td>
<td>Elastic</td>
</tr>
</tbody>
</table>

\( a \) Teflon yield stress is 25 MPa, with elastic—perfectly plastic behaviour assumed.

2.3. Finite element modelling

The experimental results were supported by finite element simulations using commercial software (ABAQUS v6.5). The simulations were used to plot out the maximum principal stresses for the different geometries. The magnitudes and locations of the maximum principal stresses were used as an indication of the order in which the specimens were most likely to fail. Details of the FEM procedures, using ABAQUS v6.5 software, have been well documented [8,9]. The curved specimen model has a 12 mm inner diameter and thickness of 1 mm, and the support thickness \( h \) below the hemispherical base of 6 mm. In this case, \( h \) is large enough compared to the glass layer thickness \( d \) for the solution to be independent of the dimensions \( h \), and the substrate can be regarded as a half space [10,11]. Properties of relevant materials for input into FEM are shown in Table 1. Contact was assumed to be frictionless. The meshes were systematically refined, particularly in the critical region (glass coating), until the solutions attained convergence. The mesh consisted of up to 25,500 elements, with element size of 10 \( \mu \)m in the critical region.

3. Results

In all of the systems under consideration in this study, due to the use of a soft indenter, a majority of the initial cracks in the specimens “pop” in rapidly between the indentation area of the indenter and the margins of the specimens, accompanied by an audible click. This differs from the usual steady slow crack growth observed with a hard indenter [12,14]. However, in certain specimens in this study, the flaw that caused the initial crack can be seen, as in Figs. 3(b) and 4(a). In some cases the initial crack grows from flaws in the margins of the specimens, as shown in Fig. 3(b) for a tapered specimen with \( L_T = 2.3 \) mm, \( t = 0.5 \) mm. The square in Fig. 3(b) indicates the margin flaw growing before the crack pops. Note that no cracks can be seen in Fig. 3(a). In some specimens (outside tapered) a crack grows from a flaw on the under-surface of the glass on the sidewalls outside the indentation area, as shown in Fig. 4(a). These cracks grow to a critical size ranging up to a few millimeters (Fig. 4(b)) before the crack pops to span between the indentation area and the margins of the specimen as shown in Fig. 4(c).
Fig. 3. Contact fractures in epoxy-filled glass shells of thickness \(d=0.5\) mm, \(L_S=2.3\) mm and \(t=0.5\) mm. Indented along the axis of symmetry with Teflon flat indenter load \(P\): (a) 500 N, (b) 1600 N and (c) 1620 N. Showing crack popping from a margin flaw. Square in (b) indicates the margin flaw growing steadily before the crack pops.

Fig. 5 highlights the mean effect of using soft indenters on contact damage in glass/epoxy bi-layer specimens, in comparison with the use of hard indenters. In both cases the glass under-surface was sandblasted. Fig. 5(a) and (b) compares radial crack patterns from single-cycle indentation of curved specimen, \(r_s=6\) mm of the same coating thickness \(d=1\) mm with a WC sphere (hard indenter) of 4 mm radius [12]. In this case the radial cracks initiated within the contact area, directly under the indenter. The radial cracks grew steadily with increasing load to the point where they became unstable, then propagated abruptly to the margins (Fig. 5(b)). An example of failure mechanism using soft indenters is shown in Fig. 5(c) and (d). In this case cracks have spread between the indentation area and the margins of the specimen. No crack initiated or extended to the top of the dome. The final crack pattern for the \(L_T=4\) mm tapered specimen (Fig. 5(d)) closely resembled the shape of semi-lunar failures seen in clinical cases of dental crown failures (Fig. 1). The mechanism of crack growth was that a margin crack grew up to the indentation area of the specimen, then two secondary cracks grew down either side of this crack to the margins, forming the pattern shown in Fig. 5(d). It is noteworthy that the radial crack densities tend to be higher for specimens indented with a soft indenter than for specimens indented with a hard indenter (compare Fig. 5(b) with (d)). Note that twice the load was applied in Fig. 5(d) \((P=2000\) N) as in Fig. 5(b) \((P=1000\) N).

Fig. 4. Contact fractures in epoxy-filled glass domes of inner radius 6 mm, \(d=0.5\) mm, \(L_S=2.3\) mm and \(t=0.5\) mm. Indented at axis of symmetry with Teflon indenter at load \(P\): (a) 600 N, (b) 620 N and (c) 650 N. Showing failure from radial cracks. Note crack initiation location i.e. from flaw half way between indentation area and the edge of the specimen.
Critical loads ($P_R$) to initiate subsurface radial cracks responsible for the structure failure in the curved glass surfaces were measured as a function of skirt geometry. The experimental results for $P_R$ are plotted in Fig. 6 as a function of taper length ($L_T$), and as a function of taper thickness ($t$) in Fig. 7. The dotted curves are predicted values from FEM using a critical stress criterion as described previously [8,9], for cracking initiating at the margins. In each case, the result indicates that increased loss of coating material through tapering of the specimen skirt (i.e. increased $L_T$ or decreased $t$) is detrimental to the capacity of the structure to bear load without incurring damage.

The result from FEM simulations of maximum principal stresses at an applied load of $P = 1500$ N are shown in Figs. 8 and 9, for the variables adapted in this study. Fig. 8

![Critical loads to initiate radial cracks ($P_R$) versus height of taper ($L_T$). The dotted curve indicates critical load predictions from FEA.](image)

![Critical loads to initiate radial cracks ($P_R$) versus minimum width of taper ($t$). The dotted curve indicates critical load predictions from FEA.](image)
shows the effect of the taper length ($L_T$) on the stress distributions. The plots clearly show the effects of using soft indenters and the taper length. Of primary interest is the extended tensile region outside the contact zone towards the base of the specimen, with peak values on the hemisphere underside and at the margin. Generally, the longer the taper length, the higher the margin stress, which implies a lower critical load for margin cracking. This is in agreement with the experimental observations of the tapered specimens (Fig. 6). It is also an intuitive result, since it is to be expected that greater material loss from the longer taper would lead to higher stresses. However, there is significant tensile stress along the underside of the entire coating away from the contact zone, indicating that the presence of a larger flaw anywhere in this area could cause crack initiation as observed experimentally in Fig. 4(a).

Fig. 8. Results from ABAQUS simulations demonstrating the effect of taper length ($L_T$) on maximum principal stresses for tapered skirt specimens near the margins. Stresses are plotted at a load of 1500 N for (a) $L_T = 0$ mm (un-tapered) and (b) $L_T = 4$ mm (entire skirt).

Fig. 9. Results from ABAQUS simulations demonstrating the effect of taper width ($t$) on maximum principal stresses for tapered skirt specimens near the margins. Stresses are plotted at a load of 1500 N for (a) $t = 0.5$ mm and (b) $t = 0.2$ mm. Note that both specimens have the same taper length, $L_T = 4$ mm.
Fig. 10. Results from ABAQUS simulations showing the maximum principal stresses along the underside of the coating, measured as a function of position coordinate \( S \) (see Fig. 2), for a specimen with taper length \( L_T = 4.0 \text{ mm} \) and \( t = 0.5 \text{ mm} \) and loads of 100 N, 500 N, 1000 N and 1500 N.

Fig. 9 shows the effect of skirt taper width on maximum principal stresses for specimens having the same taper length. As in the case of varying taper length \( (L_T) \), varying taper thickness \( (t) \) did not significantly affect the stresses in the hemispherical portion of the coating. The effect is more evident near the margins, where the specimen with the narrower taper clearly shows a higher margin stress than the less tapered sample.

Finally, Fig. 10 shows the maximum principal stresses along the underside of the coating (at the interface between the coating and the support layer, measured as a function of position coordinate \( S \), as shown in Fig. 2) for a specimen with taper length \( L_T = 4.0 \text{ mm} \) and \( t = 0.5 \text{ mm} \). Several points are worthy of note. At low loads, there are significant tensile stresses developed directly under the indenter, which are then engulfed as the soft indenter deforms and a compressive zone develops underneath it. The stress at the margin increases linearly with applied load, of the order of the peak stress in the coating, and there is significant tensile stress in the intermediate zone. The inclined dashed line represents a secondary stress peak in the hemispherical part of the coating, of similar magnitude to the stress at the margin at high loads.

4. Discussion and conclusions

The effect of skirt geometry on failure of brittle dome structures from axial loading with soft indenters has been investigated. The results show that variable skirt geometry (taper length and width) not only has an effect on critical loads to initiate the first radial crack, but also on the evolution of failure (cracks initiation locations and subsequent propagation to failure). Most prior studies have been conducted on flat bi-layer specimens [1–3,11,15–18] or, more recently, on curved dome structures with glass coatings [5–9,12–14]. In those studies the confined contact between hard indenter and brittle surface favoured a flexural mode of fracture, leading to dominant radial cracks or near-contact cone cracking (Fig. 5(a) and (b)). It is clear from those studies that specimen curvature enhances failure. In certain circumstances, dental crowns (dome structures) may become more susceptible to cracks initiating from the margins rather than from directly under the indenter (Figs. 3 and 4). This effect is enhanced in loading with soft indenters. Such indenter materials may be considered to resemble some of the properties of food bolus in chewing.

The results of this study indicate that a dental crown geometry consisting of long, thin tapers at the margins should be avoided if possible. Trends indicate that the narrower a taper is, the lower the critical load (Fig. 7). The longer the taper length of tapered samples is, the lower the critical load (Fig. 6). These relationships, while not strongly affecting the critical loads, were consistently demonstrable. They were also confirmed by finite element analysis, where an increase in maximum principal stress for a particular geometry was indicative of a lower critical load (Figs. 8 and 9). The observation of margin cracks originating from flaws at the margins in some samples suggest that a tapered margin geometry on dental crowns, in addition to a soft indenting medium, could be a contributing factor to semi-lunar failures observed in clinical cases (Fig. 1).

FEM plots show that cracks originating from areas other than the margins are feasible, since there is significant tensile stress along the coating underside away from the indenter. Indeed, there is a secondary stress peak in the hemispherical part of the coating as indicated in Fig. 10 by a dashed line. Since the stresses in this part of the coating are not significantly affected by taper length or width, application of the same critical stress criterion used to create the predictive curves for margin cracking in Figs. 6 and 7 results in a predicted critical load of 1230 N. This predicted load is likely to be lower than expected in reality, since it does not take into account the greater likelihood of larger flaws (due to grinding) near the margins. Nevertheless, the extended tensile area on the coating underside is consistent with the experimentally observed variations in initiation locations (Figs. 3(b) and 4(a)) and the secondary cracks which originated in that region and ultimately linked with the initial cracks to form a “lunar crack” failure pattern (Fig. 5(d)). This large tensile area could also provide an explanation for the scatter observed in critical loads.

Parameters other than \( t \) and \( L_T \) may have influenced the critical loads for the tapered specimens (see scatter of the data in Figs. 6 and 7). An example of one such parameter was an irregularity in the shape of the hemisphere due to manual manufacturing of the specimens, such that the hemisphere “bulged” outwards. Finite element simulations suggested the influence of this irregularity was a lowering of the critical load. Residual stresses in the glass caused by shrinkage of the epoxy resin during solidification may have also lowered the critical loads. This stress would be more severe in specimens with a larger volume of epoxy resin, i.e. \( L_S = 4 \text{ mm} \). The extent to which such parameters affected the individual specimens could account for the scatter in the critical loads.
As can be seen from this study and the previous studies [6–10,12,13,20], it is necessary to consider all the variables in the design of brittle coating layered structures such as dental crowns, as each of the variables (e.g. coating thickness, skirt geometry, modulus mismatch, indenter size and material stiffness) has a significant effect on one or more of the critical conditions and on the evolution of damage in these systems. As such, experimental and analytical investigations based on fixing one of the key entities cannot be generalised, as the scaling of the results for different dimensions is not straightforward [6–10,12,13]. Furthermore, variation in two or more of these variables causes the behaviour of the system to become quite complex [19,20].

In this study a simple bi-layer system limited to a perfect dome structure has been chosen as representation of monolithic all-ceramic dental crowns on natural tooth dentine. The results from this study should give a general indication of failure trends in more complicated 3D crown structures. Some additional calculations incorporating the brittle cement layer between the crown and the natural tooth in the form of a tri-layer structure are currently under investigation. The issue of the shock absorbing effect of the supportive alveolar bone and periodontal ligament has not been considered in the present study to simplify the current research. These factors will influence the results, but are believed to be secondary as the coating and substrate are the main structure components. However, these factors and other variables will be considered in future studies.

Conflicts of interest

We, Anne Whitton, Tarek Qasim, Chris Ford, Xiao Zhi Hu and Mark Bush, declare that we have no proprietary, financial, professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the position presented, or the review of, the manuscript entitled, “The role of skirt geometry of dental crowns on the mechanics of failure: Experimental and numerical study”.

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