Influence of Tapered Brittle Coatings on Stresses in Layered Structures: 
Relevance to Failure of Dental Crowns 

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Abstract. This paper uses Finite Element Analysis to examine stresses in loaded curved bi-layer structures. The model system consists of glass shells, both constant thickness and tapered, filled with dental composite. These systems, simulating brittle crowns on tooth dentine, are loaded with ultra-compliant disk indenters, and hard spherical indenters for comparison, along the (convex) axis of symmetry. The resulting maximum principal stress patterns are analysed.

Previous studies have generally utilised hard spherical indenters of various radii indenting constant thickness coatings, and examined stresses leading to crack initiation. However, the peak stresses observed in this traditional contact problem – inducing surface cone cracking or flexure-induced radial cracking - occurred close to or inside the (small) contact area, and do not explain the margin failures in dental crowns commonly observed by dentists. Furthermore, the effect of varying coating thickness, especially tapering towards thinner margins, has not previously been examined. The use of an ultra-compliant indenter distributes the indentation force over a large contact area, generating a compressive zone underneath the contact, and consequently, previously insignificant stresses at the support margin become dominant, and the focus shifts to the support margin, rather than the area close to the contact.

In this study, balsa wood is used as the disk indenter model material, with a modulus several orders of magnitude lower than the indented materials. Stress patterns from the same systems indented by hard spherical indenters are included for comparison. The specific focus is the effect of tapered coatings, examining stress patterns from several geometries. Results confirm not only a shift in the peak maximum principal stress from the near-contact area (under hard spherical indenters) to the margin area (under ultra-compliant indenters), but also show that coating taper can have a significant influence on the margin stress under a soft indenter. In the same systems indented by a hard indenter, coating taper has very little effect on the more localised stresses induced.

Introduction

Many systems make excellent use of brittle coatings on compliant substrates, in a wide range of engineering applications [1] and biomechanical structures [2]. 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. It has been well documented that under hard indenters, radial cracking at the coating under-surface, from flexure induced by concentrated loads at the top surface, has been identified as the most deleterious for system survival [3].

Whereas many studies have investigated damage modes in brittle/compliant bi-layers of the kind under consideration here, virtually all have concentrated on indentations with hard spheres [2-5]. These studies have enabled the identification of various damage modes and the effect on stress fields of geometrical variables such as coating thickness, indenter radius and sample radius [1-5, 7, 8], as well as material properties such as interlayer elastic modulus. Any complete analysis of structure failure requires the incorporation of these elements. However, most engineering contact
problems exhibit a higher degree of complexity. For example, occlusal loading in dental crowns is a special case in point. The reality is generally far from the “idealized” loading of relatively compliant (less stiff) objects with uniform layers and radius, contacted by a hard object (spherical indenter). However, due to the massive number of variables involved, an exhaustive series of tests is impossible. Furthermore, experimentation, while an essential part of the process of gaining knowledge, can be misleading due to natural variation in the sample being tested.

A simple examination of stresses induced under varying contact conditions using Finite Element Analysis (FEA) can provide valuable insight into the effect of different variables, without the need to interpret results accounting for experimental error. This study examines the effect of coating thickness variation on stresses in glass coatings on dental composite substrates. Both coating taper (from top thickness of 1mm to margin thicknesses of 0.5mm and 0.25mm) and a simple form of margin chamfering (45°) are considered, as shown in Fig. 1.

Previous studies [4,5,8] have demonstrated that specimen surface curvature can have a significant effect on the stress distribution in curved brittle coatings under hard indenters. The present study considers the effect of variable coating geometry (coating taper) and softer indenters on the maximum principal stresses in convex brittle layer specimens. It is shown that coating taper has very little effect under a hard indenter, where the stress is concentrated close to the small load area. However, under a soft indenter, which generates a large indentation area, coating taper can have a large effect on the stresses induced.

Analysis method

The commercial FEA package ABAQUS (version 6.5-1) was chosen to perform the analyses. The indented sample consisted of an extended dome of outer radius 7mm and skirt height 3mm, while the indenter was either a cylinder of radius 6mm and height 12mm, or a rigid hemisphere of radius 4mm. Input material properties and geometries were chosen to mirror concurrent experimental work. Borosilicate glass (D263, Menze-Glaser, Germany) for the brittle coating has a Young’s modulus of 72.9 GPa and Poisson’s ratio of 0.21. Dental composite (Tetric EvoCeram, Ivoclar Vivadent, USA) with a Young’s modulus of 13 GPa and Poisson’s ratio of 0.22 was chosen as the support material, as it closely matches the properties of human dentin. Balsa wood was used for the soft indenter as in a preceding study [6], with an E= 50MPa and a Poisson’s ratio of 0.1.

The coating was initially modelled with a constant thickness of 1mm. To generate the tapered coating of thickness 0.5mm at the margin, the hemisphere forming the inner coating surface was altered to have a radius of 6.521mm, with its centre located 0.521mm below the centre of the outer surface centroid, and for the tapered coating of thickness 0.25mm at the margin, the inner surface radius was 6.697mm, with its centre located 0.697mm below the outer surface centroid. These tapered coatings, which exhibit a gradual decrease in coating thickness, were then compared with a constant thickness coating with the inner margin chamfered at 45°, effectively resulting in a reduction in coating thickness to zero at the margin, though the change was much more sudden.

The system was modelled using continuum 4-node axisymmetric elements. An element size of 100 microns was used, with the indented sample modelled by approximately 7500 elements, and the balsa wood indenter modelled by 7200 elements. The hard spherical indenter was modelled as a rigid surface. Plots of maximum principal stress were examined and analysed for directionality.
The magnitude of the maximum principal stress along the underside of the coating was then plotted for the various geometries. Previously, where only a constant coating thickness was considered, stress was plotted against the distance along the underside of the coating. However, with the changing geometries here, this distance would refer to a slightly different position in each case. Accordingly, stress is plotted against angle from the symmetry axis (through the dome centroid).

![Figure 2](image.png)

**Figure 2.** Stress plots of maximum principal stresses in a tapered coating under a hard spherical indenter (left) and soft balsa wood indenter (right). These plots are representative of the patterns observed in all of the geometries considered here.

**Results and discussion**

Figure 2 shows plots of maximum principal stresses at an applied load of 800N, for the coating tapering from 1mm at the top of the sample to 0.5mm at the margin. On the left is the stress distribution under a rigid spherical indenter, and on the right is the stress under the soft balsa wood indenter. Only tensile stresses are displayed – a darker shade indicates higher tensile stress. Visual stress distributions do not differ significantly, so only one under each indenter is shown.

The plots clearly show the effect of differing indenters. The hard indenter generates an intense peak in tensile stress at the coating underside directly beneath the indentation – a direct consequence of coating flexure; this stress causes radial cracking. The large contact area under the soft indenter, however, causes a compressive field which engulfs the tensile area seen previously, and consequently the area of peak tensile stress is shifted towards the margin.

Representative plots of maximum principal stress against angle from the axis of symmetry for forces of 100N, 200N, 400N and 800N in a 1mm to 0.5mm tapered coating are shown in figure 3, for (a) a hard rigid indenter, and (b) the soft balsa wood indenter. The peak stress under the hard indenter always occurs directly under the indentation, and increases monotonically with load. Initially, the soft indenter causes similar behaviour, but as the indenter deforms and the compressive zone forms, the stress under the indenter decreases and becomes compressive, and the margin stress becomes dominant. The magnitude of the margin stress is not significantly different in each case.

Changing the coating geometry does not change the qualitative behaviour shown in figure 2. However, the magnitude of the margin stress does change, for both indenters. Figure 4 shows the stress profile for each geometry plotted at a load of 800N, the hard indenter (left) and soft indenter (right). However, because the primary stress under the hard indenter is located where the coating is still 1mm thick, and is approximately 30 times greater than the margin stress, the primary stress region is not affected. The primary stress region under the soft indenter is close to the margin area, where the stress is affected by coating taper. Note that stress in the chamfered margin closely follows the uniform coating stress until close to the margin, but exhibits a higher peak value near the margin that any of the other cases. Under the soft indenter, the substrate is also under significant tension, limiting the coating hoop stress.
Figure 3. Maximum principal stresses along the coating underside, at various loads as shown, under a hard spherical indenter (left) and soft balsa indenter (right). Note the initial stress peak under the balsa indenter, which is engulfed by a compression zone at higher loads as the indenter deforms.

Figure 4. Tensile stresses along the coating underside at 800N, for various geometries as shown, under a hard spherical (left) and soft balsa indenter (right). Note the initial stress peak under the balsa indenter, which is engulfed by a compression zone at higher loads as the indenter deforms.

Conclusion

The present study shows the effect of a tapered coating under a soft indenter, with thinner coatings exhibiting increased hoop stresses. A similar increase occurs under a hard spherical indenter, but is not significant since the primary stress region (under the indenter) is not affected by the taper. The stress increase is modest (around 15%), but indicates that coating taper could have a significant effect on stresses in dental crown systems, and consequently on their failure. This is particularly the case where a more compliant substrate, or layer of highly compliant cement is used, since in the present system there is a significant substrate tensile stress, limiting the “spread” of the glass coating. This will be considered in our further studies.

References

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