Published in final edited form as:

J Biomech. 2016 July 5; 49(10): 2038–2046. doi:10.1016/j.jbiomech.2016.05.003.

3D statistical failure analysis of monolithic dental ceramic crowns

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Abstract

For adhesively retained ceramic crown of various types, it has been clinically observed that the most catastrophic failures initiate from the cement interface as a result of radial crack formation as opposed to Hertzian contact stresses originating on the occlusal surface. In this work, a 3D failure

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We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome. We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed.

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prognosis model is developed for interface initiated failures of monolithic ceramic crowns. The surface flaw distribution parameters determined by biaxial flexural tests on ceramic plates and point-to-point variations of multi-axial stress state at the intaglio surface are obtained by finite element stress analysis. They are combined on the basis of fracture mechanics based statistical failure probability model to predict failure probability of a monolithic crown subjected to single-cycle indentation load. The proposed method is verified by prior 2D axisymmetric model and experimental data.

Under conditions where the crowns are completely bonded to the tooth substrate, both high flexural stress and high interfacial shear stress are shown to occur in the wall region where the crown thickness is relatively thin while high interfacial normal tensile stress distribution is observed at the margin region. Significant impact of reduced cement modulus on these stress states is shown. While the analyses are limited to single-cycle load-to-failure tests, high interfacial normal tensile stress or high interfacial shear stress may contribute to degradation of the cement bond between ceramic and dentin. In addition, the crown failure probability is shown to be controlled by high flexural stress concentrations over a small area, and the proposed method might be of some value to detect initial crown design errors.

1.Introduction

There is an increased public demand for restorations that look like natural teeth. Ceramic crowns are more biocompatible and more esthetic than metal-based restorations. However, ceramics are brittle, and failure from fracture continues to be a major concern particularly on posterior teeth which are subjected to greater masticatory loads and more continuous function. Several high strength ceramic materials have become available and are being used in dental practices^[6,8]. Their superior fracture resistance, good esthetics, and new processing methods make them suitable for thin-walled monolithic crown applications similar to metal^[15].

These materials are often introduced into the market without a basic understanding of their clinical performance because long term controlled clinical trials are not required and are both time-consuming and expensive. The development of well-designed experiments and mathematical modeling methods could be useful to help predict long term clinical survival of these new restorative techniques.

The fractographic analyses of clinically failed early ceramic crown materials such as fluormica glass-ceramic (Dicor) showed that a large percentage of the failures due to fracture initiated from the intaglio surface directly below wear facets^[10,11,19,22]. For higher strength ceramic materials such as lithium disilicate glass-ceramic, zirconia^[17] and alumina^[18], failure initiation from the intaglio surface originating in margin area has been reported. While the exact fracture initiation sites appear to depend on specific materials properties, these fractographic studies indicate that the most current ceramic crown failures initiate from the cement interface as opposed to the occlusal surface. In addition, degradation of dentin/adhesive bond^[4] and mechanically-assisted crack growth of dental ceramics in water^[23] are known to play roles in adhesive cement-retained ceramic crown failure process.

In the dental literature, a number of 3D FE models have been constructed. Della Bona et al.^[7] analyzed core/veneering porcelain crown and found that the maximum principal stress is highest at the intaglio surface of the core, in the area directly opposed to the load site and in the external surface of the veneer. De Jager et al.^[9] also analyzed core/veneering porcelain crown. It has been shown that the stress distribution can be significantly altered by stiff core material. The increased longevity with stiffer core material has been demonstrated in long-term clinical studies^[13] as expected by these FEA models.

In addition to these stress calculations, failure probability analyses including software such as CARES^[16] have been employed to predict lifetime of dental restorations such as bridges and bilayer crowns by Annusavice et al.^[2]. The analysis is based on the maximum principal stress distribution throughout the restoration. The novelty of their work^[2] exists in examining the effect of the core/veneer thickness ratio and oblique load direction on time-dependent failure probability. In analyzing failure probability specifically initiating from the intaglio surface, however, the maximum and the minimum normal stress components parallel to and directly on the intaglio surface (as opposed to the maximum principal stress) become of primary importance to fracture initiation. Currently, failure prediction mathematical modeling methods for interface-initiated failures of monolithic ceramic crowns which incorporate the biaxial nature of flexural stress components at the intaglio surface has not been established.

Some preliminary investigations have been performed based on axisymmetric flat samples. Experimentally determined surface flaw size distribution and FE stress calculations are combined on the basis of fracture mechanics based statistical failure probability model to predict failure probability distribution. The theoretical predictions are verified against experimental failure probability data based on single-cycle indentation tests on flat samples^[24,25]. Using experimentally determined ceramic fatigue data, this method is extended to predict lifetime under cyclic loadings^[12].

While simplification of geometry was useful in achieving scientific understanding of various fundamental physical factors contributing to failures, axisymmetric models are limited. For example, tooth restoration failure in the cervical margin in approximal area^[17] cannot be represented by axisymmetric models. The use of actual crown geometries becomes important in developing experimental and modeling protocol for assessing clinical longevity.

2. Methodologies

2.1 Overall approach

The overall approach of this work is schematically summarized in Figure 1. The surface flaw distribution parameters are determined by biaxial flexural tests on ceramic plates, and point-to-point variations of multi-axial stress state at the intaglio surface are obtained by FE stress analysis. By combining them on the basis of fracture mechanics based statistical failure probability model, failure probability of a monolithic crown subjected to single-cycle indentation load is predicted.

Following the work of Chao and Shetty^[5], the crack density function denoted by N (the number of cracks with critical stress, σ_{cr} per unit area) is represented in the form,

$$N = k\sigma_{cr}^m, \quad (1)$$

where m and k are the surface flaw distribution parameters. Details of the experimental determination of m and k based on biaxial tests are summarized in Wang et al.^[24]. In this work, borosilicate glass with the value of $m=4.917$ and $k=2.361(10^{-11})$ [$\text{mm}^{-2}\text{MPa}^{-4.917}$] experimentally determined by Wang et al.^[24] is employed for all simulations.

In verifying the developed method against experimental data, single-cycle indentation tests on flat axisymmetric trilayer models^[24] are used. Failure load is defined as the load at which a radial crack could be observed originating from the cement interface under transillumination and magnification ($10\times$ stereomicroscope). The transparent nature of borosilicate glass provides a ceramic substrate that allows for optimum observation of small radial crack formations that occur well before any catastrophic fractures of the glass are observed. In order to verify the developed 3D failure probability model against the experimentally verified axisymmetric trilayer model, borosilicate glass is employed as a model ceramic crown material. Furthermore, in order to examine the effect of geometrical differences on critical fracture area and failure probability, the same material properties are employed. While borosilicate glass is not used for actual dental restorations, elastic material properties as well as flaw distribution parameters are somewhat similar to some traditional dental ceramic material such as fluormica (Dicor) and Leucite reinforced glass-ceramics (Empress).

Digitized image processing—Image processing software SimpleWare^[20] is used to create a solid model from stl files generated from an optical scan (Model 800, 3Shape) of a prepared tooth, and the generated crown design from the design software (3Shape). First, the scanned images are imported to SimpleWare^[20] where the prepared tooth and crown were merged into one solid model. Secondly, using ScanIP module, a cement layer with 0.1 mm thickness is created between the crown and the prepared tooth surface simulating clinical practice, and an indenter ball is created to simulate indentation tests. Thirdly, using 10-nodes quadratic tetrahedron elements, the solid model is discretized in FE module of SimpleWare.

Accurate stress state evaluation at the intaglio surface is important in examining interface-initiated failure probability. In order to identify all the intaglio surface nodes, 6-nodes quadratic shell elements with negligible thickness ($1\text{E-}6$ mm) are attached at the ceramic with nodal points of shell elements coinciding with those of 10-nodes quadratic tetrahedron elements of ceramic and cement layer. After identification of the intaglio surface nodes, shell elements are removed using ScanIP module. Stress components at these surface nodes without shell elements are shown to be identical to those calculated with shell elements intact. Since shell elements which are part of ceramic do not impact calculation results, a mesh with shell elements is employed for further calculation. The final model is exported to FE software, ABAQUS^[1].

2.2 Finite Element Stress Calculation

Tooth Restoration—Material properties of ceramic, cement, dentin and indenter are specified in Table 1^[24], and the fixed boundary condition is specified at the bottom of the restored tooth. The indenter ball of mm diameter is placed on the top surface of the tooth restoration so that there are three contact points between the indenter and the crown by visually confirming a vertical axis. The global coordinate set of the entire model has been established by setting the origin at the center of indenter ball. The magnitude of a vertical point load applied to the center of the spherical indenter is varied from zero to maximum 4500N so that the failure probability reaches 99.9%. Idealized contact condition with no friction is employed as the load is increased.

Figure 2 shows a printout of the actual layered model used and a schematic diagram showing the various layers represented. Mesh quality satisfying all criteria available in ABAQUS^[1] is employed, and the convergence of results with mesh density is checked. Total of 1,087,457 tetrahedron elements (element type C3D10) and 60,758 shell elements (element type STRI65) with element area varying from 627 [μm^2] to 651 [μm^2] are employed.

In order to examine the effect of bond quality on the stress state and failure probability, simulations of the following four conditions are carried out.

1. Completely bonded
2. Completely debonded between ceramic and cement layer with frictionless contact
3. Partial Degradation: Represented by a completely bonded case with the cement layer modulus E reduced to 0.01% of the original value at the axial wall and margin area 1.58 mm occlusal to the restoration margins
4. Uniform Degradation: Represented by a completely bonded case with the cement layer modulus E uniformly reduced to 0.01 % of the original value throughout the intaglio surface

In interpreting the stress state, ceramic thickness variation may become important. For this purpose, the shortest distance between a nodal point at the intaglio surface and nodal points on the crown top surface is determined and used as approximate local crown thickness. The stress state is plotted using 3D plotting software, Tecplot 360[version 2013R1]^[21].

Axisymmetric Flat Samples—Wang et al.^[24] developed failure probabilistic algorithm applicable only to axisymmetric flat restorations. To verify the 3D algorithm, the biaxial flexural tests were reanalyzed using 3D models, and the results were compared with those from the axisymmetric models^[24]. For this purpose, stress analyses using 3D FE elements become necessary. The indenter ball with 40 mm diameter is modeled as analytical rigid, and total of 182458 tetrahedron elements and 30125 shell elements is used for flat samples.

Interfacial Stress State at the Intaglio Surface—For accurate evaluation of interfacial stress state, a local xyz coordinate system is introduced to each shell element with the z axis perpendicular to the intaglio surface through coordinate transformation of global coordinate

system. The interfacial normal stress at the intaglio surface is then represented by σ_{zz} . The maximum and the minimum normal stress components parallel to the intaglio surface and the interfacial shear stress, represented by $\sigma_{1, \text{parallel to the intaglio surface}}$, $\sigma_{2, \text{parallel to the intaglio surface}}$, and $\tau_{\text{interface}}$, respectively, can be evaluated based on the stress components represented in terms of local coordinate system attached to each shell element as follows.

$$\sigma_{1, \text{parallel to the intaglio surface}} = \frac{(\sigma_{xx} + \sigma_{yy})}{2} + \left(\sqrt{\frac{(\sigma_{xx} - \sigma_{yy})^2}{2} + \sigma_{xy}^2} \right) \quad (2)$$

$$\sigma_{2, \text{parallel to the intaglio surface}} = \frac{(\sigma_{xx} + \sigma_{yy})}{2} - \left(\sqrt{\frac{(\sigma_{xx} - \sigma_{yy})^2}{2} + \sigma_{xy}^2} \right) \quad (3)$$

$$\tau_{\text{interface}} = \left(\sqrt{\sigma_{zy}^2 + \sigma_{xz}^2} \right) \quad (4)$$

2.3 Post Processing

Failure Probability—Based on Batdorf and Crose^[3], the failure probability under multi-axial stress states, P_f for surface area A with crack density distribution, $N(\sigma_{cr})$, is given by

$$P_f = 1 - \exp \left[- \int_A \int_0^{\sigma_{cr}^{\max}} \frac{\Omega}{2\pi} \left(\frac{dN(\sigma_{cr})}{d\sigma_{cr}} \right) d\sigma_{cr} dA \right]. \quad (5)$$

As shown in Figure 3, under the critical normal stress fracture criteria, $\sigma_n > \sigma_{cr}$, Ω in Equation (5) is related to critical crack orientation angle, θ_{cr} , by Equation (6).

$$\Omega = 4\theta_{cr} \quad (6)$$

Equation (5) is used to evaluate the survival probability of shell element i , attached to the intaglio surface. Within each quadratic shell element with surface area A_i , stress varies linearly. However, the variation of stress components at different integration points is found to be less than 0.005% since shell element size is chosen to be small. Based on this, the stress state within each shell element is approximated by the average of stress components calculated at three integration points. Given constant maximum and minimum normal stress components parallel to the intaglio surface, represented by σ_{1i} and σ_{2i} for element i , the integration with respect to critical stress σ_{cr} in Equation (5) is replaced by summation of 100 small segments. The number of segments larger than 100 yielded the same numerical results and therefore 100 segments are used. Noting that the maximum critical stress is σ_{1i} for

element i , critical stress increment and σ_{crj} and j critical stress for shell element i , σ_{crj} are written as follows.

$$\Delta\sigma_{cr_i} = \frac{\sigma_{1_i}}{100}, \quad \sigma_{cr_{i,j}} = j(\Delta\sigma_{cr_i}), \quad \text{where } j=1, 2, 3, \dots, 100 \quad (7)$$

Based on the normal critical stress fracture criteria, critical crack orientation angle, $\theta_{cr_{i,j}}$ corresponding to $\sigma_{cr_{i,j}}$ can be calculated by

$$\theta_{cr_{i,j}} = \frac{1}{2} \cos^{-1} \left[\frac{2\sigma_{cr_{i,j}} - \sigma_{1_i} - \sigma_{2_i}}{\sigma_{1_i} - \sigma_{2_i}} \right]. \quad (8)$$

Combining Equations (1), (6), (7) and (8) on the basis of Equation (5), the survival probability of shell element i , denoted by P_{s_i} can be evaluated by

$$P_{s_i} = \exp \left[-\frac{2km}{\pi} \Delta A_i \Delta\sigma_{cr_i} \sum_{j=1}^{j=100} \{ \theta_{cr_{i,j}} (\sigma_{cr_{i,j}})^{(m-1)} \} \right]. \quad (9)$$

The overall failure probability initiating from the intaglio surface is given by

$$P_f = 1 - \prod_{i=1}^N P_{s_i}, \quad (10)$$

where N is the number of shell elements. A Matlab code is written based on Equations (9) and (10), and overall failure probability at a given indentation load is evaluated. This simulation is repeated by increasing indentation loading until the failure probability reaches 99.9%.

3 Results

3.1 Verification using axisymmetric flat samples

As shown in Figure 4, the 3D algorithm outlined in Section 2.3–2.4 reproduced theoretical failure probability predictions for 2D axisymmetric restoration samples with completely bonded and completely debonded cases^[24]. The 3D failure probability algorithm, therefore, is verified. As discussed in Wang et al.^[24], the comparison of theoretical failure probability prediction against experimental data demonstrates excellent match for the completely debonded case and less complete match for the completely bonded case. This may be attributed to surface crack bridging or residual compressive stress caused by polymerization shrinkage of the resin^[14], which are not included in the current model and more likely to be affective at the lower applied stress levels.

3.2 Human tooth restoration

3.2.1 Effect of bond conditions on failure probability distribution—The failure probability distributions for human tooth restorations are shown in Figure 5(a). In Figure 5(b) and (c), respectively, contact regions between the indenter and the ceramic for the completely bonded case with the ultimate failure load of 4500N and the thickness distribution of crown plotted on shell elements are shown.

As in flat samples, the interfacial bonding condition has a significant impact on the failure probability distribution for actual human tooth restorations as shown in Figure 5(a). The ultimate failure load (99.9% failure probability) for the completely bonded case is 4500 N. For the partial degradation model, the ultimate load reduces to 2500 N. With the uniform degradation, the ultimate load reduces to 1800 N and for completely debonded case, it becomes 1100 N.

3.2.2 Effect of bond conditions on stress state at the intaglio surface at ultimate failure load—In Figure 6, the stress state at the intaglio surface for four different interface conditions at corresponding ultimate failure load are shown on shell elements.

(a) Fracture initiation (flexural) stress: The high flexural stress area for the completely bonded case occurs in the wall area where the crown thickness is relatively thin (see Figure 6(a) top and Figure 5(c)). The partial degradation model shows increase in flexural stress at the axial wall and margin region. For the uniform degradation model, the high flexural stress region shifts to the margin region and resembles that for the completely debonded case.

(b) Interfacial normal (peeling) stress: The high interfacial normal stress area is observed throughout the margin region for the completely bonded case. With both partial and uniform degradation models, the high interfacial normal stress still occurs in margin area. For the completely debonded case, the interfacial normal stress is entirely compressive.

(c) Interfacial shear stress distribution: For the completely bonded case, the high interfacial shear is located at the wall region of the high flexural stress. While interfacial shear is not involved with ceramic fracture, the region with high interfacial shear stress may experience accelerated chemomechanical interfacial bond degradation under actual clinical situation. The partial degradation model shows a high interfacial shear stress region in close proximity to the occlusal contact areas (see Figure 5(b)). For the uniform degradation model, high interfacial shear stress is highly localized at the occlusal table region.

(d) Direction of fracture initiation stress and shear stress: In Figure 7(a) and (b), the direction of the maximum fracture initiation stress parallel to the intaglio surface for both completely bonded and completely debonded cases are respectively shown. The most likely fracture initiation direction for the completely bonded case is parallel to the contour of the margin, leading to horizontal split of the crown. For the completely debonded case, however, the most likely fracture initiation direction is perpendicular to the contour of the margin, leading to vertical split of the crown. The bonding condition, therefore, impacts not only the location of the most likely fracture initiation area but also the direction of fracture crack initiation. In Figure 7(c), the direction of maximum interfacial shear stress for the

completely bonded case is shown on the top surface of shell elements which are part of crown (see Figure 6 (c) top schematic). As expected, it is directed vertically downwards, and this holds throughout the wall region.

3.2.3 Effect of bond conditions on stress state under a 200 N indentation load

—In Figure 8, the stress state at the intaglio surface for four different interface conditions subjected to clinically relevant load, 200N, is shown on shell elements. Given the same load, it is clear that deterioration of bond condition significantly increases the magnitude of all three stress components.

3.3 Comparison of critical fracture area

In Table 2, the critically stressed area for both axisymmetric flat samples and human tooth restoration models at corresponding ultimate failure loads are compared. Despite the significant differences in terms of total interfacial area (373 mm² for human tooth restoration and 80 mm² for flat sample), the critically stressed area is almost identical and small. The minimum normal stress components parallel to the intaglio surface in critical area for all cases in Table 2 show that the stress state is more biaxial than uniaxial. Therefore, the use of biaxial flexural tests in determining surface flaw distribution parameters appears to be more desirable than three-point or four-point bending tests. The probability of failures initiating from these small critical regions is approximately 90% for all the cases considered as in Table 2. This result is not surprising since experimentally determined parameters m and k for the surface flaw distribution in Equation (1) is employed for all the cases considered, and fracture initiation is controlled only by locally high flexural stress.

4. Conclusions

1. A 3D failure prognosis model based on statistical fracture mechanics probability theory is developed for interface initiated failures of monolithic crowns. The method is verified by prior 2D model and experimental data. It is expected that this work can be extended to develop a clinically relevant fatigue life prediction model.
2. Under complete bond condition, both high flexural stress and high interfacial shear stress are shown to occur in the wall region while high interfacial normal tensile stress distribution is observed at the margin region. Significant impact of reduced cement modulus on these stress state is shown. While the analyses are limited to single-cycle load-to-failure tests, high interfacial normal tensile or shear stress may accelerate chemomechanical degradation of the bond between ceramic and dentin.
3. The crown failure probability is shown to be controlled by high flexural stress concentrations over a small area, and the proposed method might be of some value to detect initial crown design errors.

Acknowledgments

This research was supported by NIDCR grant number R56DE 021470.

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Figure 1.
Overall Approach.

Figure 2.
Human tooth restoration.

Figure 3.
A solid angle Ω enclosing all the normals to crack plane.

Figure 4. Verification of 3D predictions against 2D predictions and experimental data by Wang et.al [2006]

(a)

Figure 5.

(a) Effect of bond and cement material degradation on failure probability distributions; completely bonded sample with original cement material modulus, partial degradation with complete bond (original cement modulus at occlusal table, 0.01% of original cement modulus at wall and margin), uniform degradation with complete bond (0.01% of original cement modulus) and complete debond sample, (b) Contact area for ceramic crown at the ultimate failure load 4500N for completely bonded sample, (c) Thickness distribution of crown shown on shell elements.

Figure 6.

Stress distribution at the intaglio surface shown on shell elements at the corresponding ultimate failure loads for completely bonded sample with original cement material modulus, partial degradation model with complete bond (original cement modulus at occlusal table, 0.01% of original cement modulus at wall and margin), uniform degradation model with complete bond (0.01% of original cement modulus) and complete debond sample (a) Fracture initiation stress, (b) Interfacial normal (peeling) stress, and (c) Interfacial shear stress.

Figure 7.

Direction of the maximum fracture initiation (flexural) stress parallel to the intaglio surface and the most likely orientation of the fracture initiating surface crack for (a) completely bonded sample and (b) completely deboned sample, (c) Direction of the interfacial shear stress for completely bonded sample. All cases are shown in high stressed region.

Figure 8.

Effect of bonding condition and interfacial degradation on the stress state at the intaglio surface under 200 N indentation loading for completely bonded sample with original cement material modulus, partial degradation with complete bond (original cement modulus at occlusal table, 0.01% of original cement modulus at wall and margin), uniform degradation with complete bond (0.01% of original cement modulus) and complete debond sample (a) Fracture initiation stress, (b) Interfacial normal (peeling) stress and (c) Interfacial shear stress

Table 1

Material property and geometry

	Thickness (mm)	Elastic modulus, E (GPa)	Poison's ratio, ν
Borosilicate glass	1.15	62.5	0.19
Cement	0.1	10.21	0.33
substrate	5	12.6	0.35
Indenter ball		700	0.2

Table 2

Comparison of the critical region area A, (where $\sigma_{flexural\ stress} > 130MPa$), the maximum and minimum principal stress components parallel to the intaglio surface averaged over the corresponding critical area, and failure probability initiating from the critical region at corresponding ultimate failure loads.

	Axisymmetric (complete bond)	Axisymmetric (Complete debond)	3D (complete bond)	partial degradation	uniform degradation	3D(complete debond)
Area, A (mm ²) ($\sigma_{flexural\ stress} > 130MPa$)	2.81	2.66	2.68	2.76	2.68	2.78
Ultimate failure Load (N)	1000	500	4500	2500	1800	1100
σ_1 averaged over critical area A (MPa)	136.58	138.30	137.22	138.65	137.66	140.22
σ_2 averaged over critical area A (MPa)	128.45	129.50	127.25	125.80	125.88	128.50
Failure probability over critical area A	93.20%	89.98%	90.58%	93.30%	90.53%	92.07%