Survival Predictions of Ceramic Crowns Using Statistical Fracture Mechanics

S. Nasrin¹, N. Katsube¹, R.R. Seghi², and S.I. Rokhlin³

Abstract

This work establishes a survival probability methodology for interface-initiated fatigue failures of monolithic ceramic crowns under simulated masticatory loading. A complete 3-dimensional (3D) finite element analysis model of a minimally reduced molar crown was developed using commercially available hardware and software. Estimates of material surface flaw distributions and fatigue parameters for 3 reinforced glass-ceramics (fluoromica [FM], leucite [LR], and lithium disilicate [LD]) and a dense sintered yttrium-stabilized zirconia (YZ) were obtained from the literature and incorporated into the model. Utilizing the proposed fracture mechanics-based model, crown survival probability as a function of loading cycles was obtained from simulations performed on the 4 ceramic materials utilizing identical crown geometries and loading conditions. The weaker ceramic materials (FM and LR) resulted in lower survival rates than the more recently developed higher-strength ceramic materials (LD and YZ). The simulated 10-y survival rate of crowns fabricated from YZ was only slightly better than those fabricated from LD. In addition, 2 of the model crown systems (FM and LD) were expanded to determine regional-dependent failure probabilities. This analysis predicted that the LD-based crowns were more likely to fail from fractures initiating from margin areas, whereas the FM-based crowns showed a slightly higher probability of failure from fractures initiating from the occlusal table below the contact areas. These 2 predicted fracture initiation locations have some agreement with reported fractographic analyses of failed crowns. In this model, we considered the maximum tensile stress tangential to the interfacial surface, as opposed to the more universally reported maximum principal stress, because it more directly impacts crack propagation. While the accuracy of these predictions needs to be experimentally verified, the model can provide a fundamental understanding of the importance that pre-existing flaws at the intaglio surface have on fatigue failures.

Keywords: computer simulation, finite element analysis, mastication, mathematical modeling, stress analysis, minimally invasive dentistry

Introduction

Complete crown restoration remains the treatment most prescribed by dentists to reinforce weakened teeth. Increased patient esthetic demands have forced clinicians to move away from the use of more conservative cast metal crowns in favor of more esthetic approaches. Most esthetic restorations require additional axial reduction compared to cast metal (Rosenstiel et al. 2015). In 2009, Glidewell Laboratories introduced the BruxZir crown. This monolithic zirconia crown was offered as an esthetic alternative to metal-ceramic, at a low price, with good dimensional accuracy and a 5-y manufacturer material warranty. Perhaps the most appealing aspect of this new crown type is that it requires preparation specifications similar to those of cast metal. Despite the lack of existing clinical performance data and concerns regarding low-temperature degradation raised by some in the scientific community (Kelly and Denry 2008), many dentists have recommended and prescribed this new crown type for their patients (Makhija et al. 2016).

A recent systematic review comparing 5-y survival rates of single crowns suggests that several current all-ceramic crown types compare favorably to that of metal-ceramics when used on posterior teeth (Sailer et al. 2015). Nearly all of the ceramic crown systems examined in this analysis were layered structures. When the reasons for failure or replacement were analyzed, the relative risk of crown loss due to ceramic chipping

and fracture remained significantly higher than for metal-ceramic systems. Failures from fractures remain the primary concern for many clinicians.

The application of fractographic analysis to determine the fracture origins of crowns that have failed in service has been reported in numerous publications (Kelly et al. 1990; Thompson et al. 1994; Quinn et al. 2005; Øilo and Gjerdet 2013; Moráquez et al. 2015; Øilo and Quinn 2016). These analyses identified a number of fatigue fracture modes and the mechanisms that lead to these failures are well summarized (Zhang et al. 2013). Fractures of the outer porcelain layer resulting from contact fatigue with opposing teeth have been observed in some failed crown specimens (Moráquez et al. 2015; Sailer et al. 2015). The application of monolithic ceramic structures reduces or eliminates the potential for failures associated with porcelain layering.

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Malament and Socransky (1999) documented the long-term survival analysis of one monolithic ceramic crown system (Dicor; Dentsply International). Although this material has not been available for many years, the publication by Malament and Socransky (1999) has provided valuable insight and inspired numerous fundamental investigations. Fractographic analysis of failed Dicor crowns indicated that most fractures originated from the intaglio surface (Thompson et al. 1994). Interface-initiated fractures that originated from cervical margins have been identified as an important mode of failure for many all-ceramic systems (Quinn et al. 2005; Øilo and Gjerdet 2013; Øilo et al. 2014).

Chai et al. (1999) were the first to identify that during indentation loading, median-radial cracks can initiate from the interface away from the top surface contact zone when a brittle layer is supported by a compliant substrate. In this indentation trilayer model, interface-initiated radial fractures and near-contact surface Hertzian cone fractures can occur simultaneously and are in direct competition with each other. The trilayer model has been used to examine interface-initiated fractures under both static and dynamic loading conditions (Clelland et al. 2007; Hernandez et al. 2008). Computer modeling efforts were subsequently employed to better understand the mechanisms involved in this fracture process (Wang et al. 2006). We incorporated the methodologies developed from this previous work into the proposed methodology.

As the profession rapidly moves toward the use of high-strength, thin-walled ceramic crowns, new translucent zirconia formulations are being introduced into the marketplace without adequate clinical testing. The need for predictive models has never been greater. Various 3-dimensional (3D) finite element (FE) models of complete crowns have been reported in the dental literature. Detailed analyses have identified high-stress regions on crown surfaces under loading conditions (Della Bona et al. 2013). In addition, failure probability analysis software has been employed to predict the restoration lifetimes (Anusavice et al. 2013). These analyses have all been based on maximum principal stress distributions. In analyzing failure probability with respect to ceramic fractures, the maximum tensile stress tangential to the surface, rather than the maximum principal stress, has primary importance in the fracture process (Nasrin et al. 2016). In this work, we propose methodology that predicts the fatigue survival probability and probable fracture origin for a thin-walled monolithic ceramic crown by combining 3D FE analysis with statistical fracture mechanics-based concepts.

Materials and Methods

Material Parameters

The survival probability (Nasrin et al. 2016) under multiaxial stress states, S , for surface area A with crack density distribution, $N_{flaw}(\sigma_{cr})$, is given by Equation 1:

$$S = \exp\left[-\int_A \int_0^{\sigma_{cr}^{max}} \frac{\Omega}{2\pi} \left(\frac{dN_{flaw}(\sigma_{cr})}{d\sigma_{cr}}\right) d\sigma_{cr} dA\right] \quad (1)$$

Representing the in-plane principal stress components by σ_1 and σ_2 , under the critical normal stress fracture criteria, Ω in Equation 1 is related to critical crack orientation angle, θ_{cr} , by Equation 2:

$$\Omega = 4\theta_{cr}, \theta_{cr} = \frac{1}{2} \cos^{-1} \left[\frac{2\sigma_{cr} - \sigma_1 - \sigma_2}{\sigma_1 - \sigma_2} \right] \quad (2)$$

Crack density distribution N_{flaw} with parameters, $\bar{k}$ and m , is given as follows:

$$N_{flaw} = \bar{k} (\sigma_{cr})^m \quad (3)$$

where parameter m is identical to the widely used Weibull modulus. Fast-fracture parameters available in the literature (Myers et al. 1994 for leucite [LR]; Studart et al. 2007a for yttrium-stabilized zirconia [YZ]; Tinschert et al. 2000 for fluoromica [FM]; Joshi et al. 2014 for lithium disilicate [LD]) were employed to obtain parameter $\bar{k}$ in Equation 3 through parameter conversions based on their experimental loading condition (4-point bending, cantilever, and biaxial tests) and specimen geometry used.

We consider the cyclic fatigue of our model ceramic crown under a sinusoidal cyclic load with the maximum stress, σ_{max} , and the zero minimum stress under a mastication frequency of 1.5 Hz (time period $T = 0.667$ seconds). Based on the power law fatigue formulation (Gross et al. 1996), the stress that corresponds to initial critical crack size (prior to N cyclic loading with σ_{max}), σ_i , can be expressed as:

$$\sigma_i = \left[\frac{2^{-n} hNT (\sigma_{max})^n}{B} + (\sigma_{max})^{(n-2)} \right]^{\frac{1}{n-2}} \quad (4)$$

where

$$B = \frac{2}{AY^2 (n-2) K_{IC}^{(n-2)}}, h = \frac{1}{\pi} \int_{-\pi/2}^{\pi/2} [1 + \sin\theta]^n d\theta \quad (5)$$

In Equation 4, it is assumed that all subcritical crack growth is caused by stress-corrosion, and there is no additional damage by the act of loading and unloading such as a crack-bridging or other toughening mechanism. For YZ (Studart et al. 2007b) and LD (Joshi et al. 2014), experimentally determined Paris law-based fatigue parameters were converted to power law-based fatigue parameters (Munz and Fett 1999). For LR, experimentally determined power law-based fatigue parameters available in Myers et al. (1994) were employed. Since

Table. Fast-Fracture and Fatigue Parameters of 4 Dental Ceramic and Material Properties Employed for Simulation.

	Young's Modulus (GPa)	Poisson's Ratio	Fast-Fracture Parameter		Fatigue Parameter		Cyclic Parameter h (for 1.5 Hz)
			m	$\bar{k}$ (MPa ^{-m} mm ⁻²)	n	B (MPa ² s)	
YZ	210 ¹	0.3 ¹	10.4 ²	8.0E-33 ³	24.9 ⁴	10.796 ⁵	3.52E6 ⁵
LD	95 ⁶	0.23 ⁶	9.2 ⁷	1.42E-18 ⁸	19.1 ⁷	3839.8 ⁸	72.09E3 ⁸
LR	67 ⁹	0.21 ¹⁰	7.2 ¹¹	4.28E-16 ¹²	31 ¹¹	3.005E-2 ¹¹	217.1E6 ¹²
FM	66 ¹³	0.29 ¹³	5.5 ¹⁴	3.565E-12 ¹⁵	29.4 ¹⁶	5.895E-2 ¹⁶	73.5E6 ¹⁷
Food layer (polyethylene)	0.9 ¹⁸	0.46 ¹⁹					
Cement	10.21 ²⁰	0.3 ²⁰					
Dentin	12.65 ²⁰	0.33 ²⁰					
Indenter (brass)	105 ²¹	0.346 ²¹					

FM, fluormica; LD, lithium disilicate; LR, leucite; YZ, yttrium-stabilized zirconia.

1. Dejak et al. 2012; 2. Studart et al. 2007a; 3. Calculated based on values provided by Studart et al. 2007a; 4. Studart et al. 2007b; 5. Calculated based on values provided by Studart et al. 2007b; 6. Ivoclar Vivadent, 2015; 7. Joshi et al. 2014; 8. Calculated based on values provided by Joshi et al. 2014; 9. Rekow and Thompson 2007; 10. Gonzaga et al. 2011; 11. Myers et al. 1994; 12. Calculated based on values provided by Myers et al. 1994; 13. Sun et al. 2007; 14. Tinschert et al. 2000; 15. Calculated based on values provided by Tinschert et al. 2000; 16. Magida et al. 1984; 17. Calculated based on values provided by Magida et al. 1984; 18. Akathrem, 2016; 19. GoodFellow, 2016; 20. Wang et al. 2006; and 21. Elgin Fasteners Group, 2016.

fatigue investigations for FM were not available in the literature, fatigue parameters determined for Macor (Magida et al. 1984) were employed. Both Macor and Dicor are mica type glass-ceramics with similar crystal phases (Höland and Beall 2012). The material properties and parameters utilized for this analysis are summarized in the Table.

Computational Model and Digitized Image Processing

Following the method described previously (Nasrin et al. 2016), stl files based on the scanned images of a prepared tooth and the corresponding crown restoration were imported into image processing software (Simpleware Ltd 2015). A cement layer (0.1-mm thickness), an indenter ball (6.25-mm radius), and a simulated food layer (0.2-mm thickness) were created with a rigidly adhered interface between food and the occlusal surface and with a sliding interface between food and the indenter. Ten-node quadratic tetrahedron elements were used to digitize the solid model and 6-node quadratic shell elements with negligible thickness (1E-6 mm) were attached to the intaglio surface to identify all of the intaglio surface nodes. The final model was exported to Abaqus FE software (Dassault Systèmes 2013).

FE Stress Calculation

Figure 1 presents an FE mesh and a corresponding schematic diagram showing the various layers. The material properties shown in the Table and the fixed boundary condition at the bottom of the restored tooth were employed. A vertical point load of 500 N was applied to the spherical indenter with no friction between the food layer and the indenter. A maximum bite force of 500 N (average masticatory force of ~100 to 200 N) was chosen to ensure that our lifetime estimates were very conservative. After checking mesh quality and the convergence, a total of 1,108,235 tetrahedron elements (element type C3D10) and 60,788 shell elements (element type STRI65) were employed. To assess the influence of interface bonding on survival

Figure 1. A human tooth restoration model.

probability, simulations were conducted for (a) the completely bonded case and (b) the completely debonded case (frictionless contact between the crown and cement layers). The stress state was plotted using Tecplot 360 3D software (Tecplot 2013).

The maximum and the minimum tensile stresses tangential to the intaglio surface and the interfacial normal and shear stresses were evaluated in terms of a local coordinate system attached to each shell element.

Clinical Survival Rate Simulation

The shell element was chosen to be small, and the stress state within each shell element was approximated by the average of stress components calculated at 3 integration points. Under a simulated mastication load, each shell element e was subjected to sinusoidal cyclic stress with the maximum and minimum tensile stresses tangential to the intaglio surface represented by σ_{1e} and σ_{2e} , respectively, and the zero minimum stress. Crack size grew after N cycles, and a significant reduction of critical stress for fracture initiation occurred. Using Equation 4 to

Figure 2. Fatigue survival probability for 4 dental ceramic crowns under mastication load with complete bond and complete debond cases. FM, fluoromica; LD, lithium disilicate; LR, leucite; YZ, yttrium-stabilized zirconia.

evaluate critical stress components prior to fatigue, represented as $\sigma_{1e,initial}$ and $\sigma_{2e,initial}$, we obtained:

$$\sigma_{1e,initial} = \left[\frac{2^{-n} hNT(\sigma_{1e})^n}{B} + (\sigma_{1e})^{(n-2)} \right]^{\frac{1}{n-2}}, \quad (6)$$

$$\sigma_{2e,initial} = \left[\frac{2^{-n} hNT(\sigma_{2e})^n}{B} + (\sigma_{1e})^{(n-2)} \right]^{\frac{1}{n-2}}$$

In evaluating the fatigue survival rate for each element, Equation 1 was employed, in which the integration with respect to critical stress was replaced by summation of 100 small incremental segments as follows:

$$\Delta\sigma_{cr_e} = \frac{\sigma_{1e,initial}}{100}, \sigma_{cr_{e,j}} = j(\Delta\sigma_{cr_e}) \quad (7)$$

where $j = 1, 2, 3, \dots, 100$. The critical crack orientation angle $\theta_{cr_{e,j}}$ corresponding to $\sigma_{cr_{e,j}}$ was calculated by replacing σ_1 , σ_2 , and σ_{cr} in Equation 2 with $\sigma_{1e,initial}$, $\sigma_{2e,initial}$, and $\sigma_{cr_{e,j}}$, respectively. Combining Equations 2, 3, 6, and 7 on the basis of Equation 1, the survival probability of shell element e after N cycles of fatigue, S_e , was given by:

$$S_e = \exp \left[-\frac{2m\bar{k}}{\pi} \Delta A_e \Delta\sigma_{cr_e} \left\{ \sum_{j=1}^{j=100} \theta_{cr_{e,j}} (\sigma_{cr_{e,j}})^{(m-1)} \right\} \right] \quad (8)$$

The overall failure probability initiating from the intaglio surface was given by:

$$S = \prod_{e=1}^M S_e \quad (9)$$

where M in Equation 9 represents the number of elements. A Matlab code was written based on Equations 8 and 9, and the overall survival probability under a 500-N fatigue load was evaluated.

Most Likely Fracture Initiation Sites for LD and FM Crowns

To determine the most probable fracture initiation site, the crown intaglio surface was divided into 2 broad areas. The occlusal table portion of the intaglio surface included all areas that were above the lowest point of the central fossa (above 1.25 mm) and the walls were considered to be all surfaces from the crown margins to 1.25 mm up the wall. Region-dependent failure probabilities were calculated based on Equations 8 and 9 for ceramic materials LD and FM. These ceramics were chosen because they are significantly different in strength and moduli, and there are published fractographic analyses of failed crowns fabricated from these 2 materials.

Results

Fatigue Survival Rates

Figure 2 shows the survival rates of thin-walled monolithic ceramic crowns with completely bonded and completely debonded intaglio surfaces for the 4 ceramic materials. Ceramic materials FM and LR resulted in lower survival rates than materials LD and YZ. For each of the ceramic materials, the survival rates of the completely debonded case were lower than those of the completely bonded crowns. The effect of bonding was more dramatic for ceramic materials LR and FM and appeared to have less of an impact on materials LD and YZ. For material YZ, the difference in predicted survival between crowns that were completely bonded and crowns that were completely debonded was so small that it was not distinguishable on the probability scale presented in Figure 2. Material YZ was predicted to have the highest survival rate among the ceramic materials evaluated.

Tensile Stress Tangential to the Interfacial Surface

Figure 3a shows a distribution map of the maximum tensile stress (tangential to the surface) profile at the intaglio surface of 4 dental ceramic materials under 500-N loading and with complete interface bonding conditions. For ceramic YZ, a relatively high average tensile stress concentration of 73 MPa was observed over a relatively small area ($\sim 0.04665 \text{ mm}^2$) located on the proximal-lingual margin region (region A). Similarly, a moderate stress concentration (average 44 MPa) was observed over a slightly greater area ($\sim 0.196 \text{ mm}^2$) on the occlusal table region (region B) located directly below the surface indentation contact areas. Although the stress magnitudes for LD, LR, and FM ceramics were lower than those for YZ, similar relative tensile stress distribution trends were observed, as would

be expected. The average stress over regions A and B was 60 MPa and 34 MPa for LD, respectively. The tensile stress distributions for LR and FM were shown to be almost identical due to the similarity in their elastic moduli. The average stress for regions A and B was 30 MPa and 21 MPa, respectively, for these 2 ceramic materials.

Interfacial Normal and Shear Stresses

Figure 3 (b, c) shows interfacial normal and shear distributions at the intaglio surface for the 4 dental ceramic materials with complete bonding conditions. For all materials, the high interfacial normal tensile (peeling) stress distribution was observed throughout the margin region and high compressive stress distribution was observed in the table region, while significant differences in stress magnitudes were observed among the 4 materials.

Most Likely Fracture Initiation Sites and Failure Modes

In Figure 4a, the wall and table initiated failure probabilities are plotted as a function of the number of loading cycles. For the 2 materials evaluated, early failures (with a small overall failure rate) were more likely to occur from wall areas near the margin (region A) where the highest (most damaging) tensile stress was located. With the increase in fatigue crack growth, failure location shifted to the occlusal table region. When the overall failure rate was large (~50% corresponding to 55,000,000 cycles for LD and 600,000 cycles for FM), most failures were initiated from the table (region B).

The maximum tensile stress (tangential to the surface) areas of the crowns were the locations where fractures were most likely to originate and/or propagate. Figure 4b shows representative volume elements from the areas of maximum tensile stress for 2 of the ceramic materials (LD and FM). The representative volume elements contain median/radial cracks that were oriented in a direction that was optimal for crack propagation. This orientation was chosen to ensure that the highest probability of fracture propagation would occur. For both materials, the direction of the median growth for the crack tip radiated perpendicular to the intaglio surface. For material LD, the critical cracks were much more likely to originate from the margin areas with the radial growth oriented in the incisal-cervical direction perpendicular to the crown margin. For material FM, the radial cracks were only slightly more likely to occur from intaglio surfaces directly under the occlusal contact loads with radial crack growth occurring in the buccolingual direction.

Discussion

Ten-year survival probability estimates of thin-walled crowns fabricated from 4 different ceramic materials were reported (Fig. 2) under a highly idealized loading condition with a maximum bite force of 500 N. Axial loading through a large sphere

Figure 3. Stress distribution at the intaglio surface shown on shell elements for completely bonded samples for 4 dental ceramics for the maximum tensile stress tangential to the surface (a), interfacial normal stress (b), and interfacial shear stress (c). FM, fluoromica; LD, lithium disilicate; LR, leucite; YZ, yttrium-stabilized zirconia.

with a simulated food layer was employed. Direct tooth-to-crown or crown-to-crown contact during swallowing and clenching or grinding at high loads in bruxing patients were neglected.

It is unlikely that any model can accurately predict actual clinical performance, since there are numerous reasons associated with crown failures not related to fracture. This model is limited to one specific failure mode. The accuracy of these predictions cannot be assessed until laboratory simulations are performed. The results of our current model suggest that the role of bonding is much more important to the survival probability of weaker ceramics (FM and LR) than it is for stronger ceramics (LD and YZ). This would support the manufacturers' recommendations that crowns fabricated from materials YZ and LD can be either conventionally cemented or bonded, whereas bonding is highly recommended for material LR.

For these crown types, we assumed that all fractures originate from flaws present at the intaglio surface at the time of cementation. The distribution of failures is highly dependent on the size and distribution of the flaw populations that exist on the intaglio surface. This assumption allows us to consider only the propagation phase of crack growth and to ignore the initiation phase. We applied fast-fracture data reported in the literature to determine parameters m and k for each material. These parameters are dependent on surface flaw distributions and can greatly influence the outcomes of the predictions. No attempt was made to ensure that the data used were obtained from specimens that accurately reflected the actual intaglio surface of a crown. Errors in these parameter estimates will

Figure 4. Region dependent overall failure probability and critical failure initiation direction. (a) Overall failure probability rate initiated from the table and wall for LD and FM. (b) Directions of the maximum tensile stress tangential to the surface and critical crack for LD (most likely failure initiation from region A after 5 million cycles) and FM (most likely failure initiation from region B after 0.6 million cycles). FM, fluorimica; LD, lithium disilicate.

alter the survival predictions. The failure probability model must also consider the material's response to fatigue from sub-critical crack growth, which is known to occur in all ceramic materials. The fatigue parameters (n , B) used in this investigation were also obtained from previously reported crack growth data. Fatigue parameters are needed to consider the extension of existing flaws from repeated stress. The parameters used were derived from various test methods, which might also introduce errors. A more critical assessment of these parameters may be needed to improve accuracy.

The methodology also allows for the possibility of predicting the probable location of the fracture initiation sites. Figure 4 demonstrates the form of the prediction estimates that result from this analysis for 2 materials. For material LD, fractures originating from the wall areas (region A) tend to dominate the failure mode until later in the life cycle (10 to 15 y), when failures from the table areas (region B) begin to become more probable. The results tend to agree with clinical reports of actual failed LD glass-ceramic crowns, which have been shown to fail from interface fractures originating near the margins (Öilo et al. 2014). For material FM, the predictions suggest that fractures originating from the wall area (region A) are either similar or slightly less probable than those from the occlusal table area (region B). Early fractographic analysis of failed Dicor crowns (similar to FM) suggested that a majority of them tended to fail from the intaglio surface (Thompson et al. 1994). To compare our results with these clinical reports, one must be reminded that the crowns from the earlier time point had much thicker wall dimensions than our proposed

crown model. In our model, if the crown wall thickness was increased, the maximum tensile stress in the wall area would be reduced for a given load; thus, the probability of fractures from this area would also be reduced. We might expect that the failure probability of the fractures originating from the occlusal table area would be much more dominant in that situation.

In this methodology, we combine the use of statistical fracture mechanics-based principals with 3D FE stress analysis to predict crown survival. Although the accuracy of the model must be further assessed, the outcomes are generally in agreement with much of what we currently understand about ceramic crown fractures.

Author Contributions

S. Nasrin, N. Katsube, contributed to conception, design, data acquisition, analysis, and interpretation, drafted and critically revised the manuscript; R.R. Seghi, S.I. Rokhlin, contributed to conception, design, and data interpretation, critically revised

the manuscript. All authors gave final approval and agree to be accountable for all aspects of the work.

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