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Time-dependent fracture probability of bilayer, lithium-disilicate-based glass-ceramic molar crowns as a function of core/veneer thickness ratio and load orientation

Kenneth J. Anusavice^a, Osama M. Jadaan^b, and Josephine Esquivel-Upshaw^a

^aUniversity of Florida, Gainesville, FL

^bUniversity of Mount Union, Alliance, OH, USA

Abstract

Recent reports on bilayer ceramic crown prostheses suggest that fractures of the veneering ceramic represent the most common reason for prosthesis failure.

Objective—The aims of this study were to test the hypotheses that: (1) an increase in core ceramic/veneer ceramic thickness ratio for a crown thickness of 1.6 mm reduces the time-dependent fracture probability (P_f) of bilayer crowns with a lithium-disilicate-based glass-ceramic core, and (2) *oblique* loading, within the central fossa, increases P_f for 1.6-mm-thick crowns compared with vertical loading.

Materials and methods—Time-dependent fracture probabilities were calculated for 1.6-mm-thick, veneered lithium-disilicate-based glass-ceramic molar crowns as a function of core/veneer thickness ratio and load orientation in the central fossa area. Time-dependent fracture probability analyses were computed by CARES/Life software and finite element analysis, using dynamic fatigue strength data for monolithic discs of a lithium-disilicate glass-ceramic core (Empress 2), and ceramic veneer (Empress 2 Veneer Ceramic).

Results—Predicted fracture probabilities (P_f) for centrally-loaded 1.6-mm-thick bilayer crowns over periods of 1, 5, and 10 years are 1.2%, 2.7%, and 3.5%, respectively, for a core/veneer thickness ratio of 1.0 (0.8 mm/0.8 mm), and 2.5%, 5.1%, and 7.0%, respectively, for a core/veneer thickness ratio of 0.33 (0.4 mm/1.2 mm).

Conclusion—CARES/Life results support the proposed crown design and load orientation hypotheses.

Significance—The application of dynamic fatigue data, finite element stress analysis, and CARES/Life analysis represent an optimal approach to optimize fixed dental prosthesis designs produced from dental ceramics and to predict time-dependent fracture probabilities of ceramic-based fixed dental prostheses that can minimize the risk for clinical failures.

Keywords

Core ceramic; Veneering ceramic; Lithium disilicate; Glass-ceramic; Load orientation; Prosthesis design; Thickness ratio; Dynamic fatigue; Finite element analysis; Stress; CARES/Life; Fracture probability

1. Introduction

Core/veneer ceramic prostheses have been increasingly accepted recently as an alternative to metal-ceramic and full-metal prostheses for single-unit and multiple-unit restorations. These ceramic-ceramic prostheses have been used without sufficient evidence of clinical safety and effectiveness, especially regarding their susceptibility to fracture. Recent publications of clinical studies have reported chipping of veneered zirconia prostheses as “technical complications” [1]. However, none of these studies has reported the precise location or size of these fractures [2]. Thus, it is not feasible to assess the most likely cause of fractures in these cases or similar cases without additional biomechanics analyses.

Although several contributing factors, such as residual tensile stress from thermal contraction effects, framework design, veneer thickness, load orientation, grinding damage, aging effects of zirconia, elastic modulus of support structures, and parafunction have been proposed as causes of these structural failures, no single factor has been proven to be the dominant cause for the majority of these fractures.

The reported reasons for ceramic-ceramic restoration fractures include veneer chipping, core fracture, and greater loading locations in the mouth, e.g., posterior tooth versus anterior tooth sites. Previous studies have shown that the probability of chipping fractures is significantly greater for ceramic-ceramic prostheses compared with metal-ceramic prostheses [1].

Based on CARES pot-processor analyses [3], Fischer et al. (2003) [4] predicted that three-unit fixed dental prostheses made from monolithic E2C glass-ceramic and loaded at 100 N on the occlusal surface of the pontic are not likely to fracture over a period of 10 years or more ($p = 0.0026\%$).

Studart et al. (2007) [5] concluded from cyclic fatigue tests that all-ceramic bridges made from a lithium-disilicate-based glass-ceramic framework (Empress 2, Ivoclar Vivadent, Schaan, Liechtenstein) and an apatite-based veneer (Eris, Ivoclar Vivadent) were not recommended for use in the molar region. This recommendation is consistent with that of Marquardt et al. (2006) [6], who reported that the susceptibility of the fluorapatite-based veneering ceramic (Eris), the successor to Empress 2 Veneering Ceramic, was associated with the release of Ca^{2+} , PO_4^{3-} , and OH^- ions when subjected to tensile stress in water.

Based on a meta-analysis, Pjetursson et al. (2007) [7] reported a failure rate over 5 years of 6.7% for ceramic-ceramic crowns, which included reinforced glass-ceramic, which can be assumed to be Empress 2 glass-ceramic. However, the specific types of ceramic used for these prostheses were not identified. The most common type of failure was chipping fracture of the veneer ceramic, which occurred in 4.5% of the crowns. When used for posterior teeth, the 5-year survival rates of densely sintered alumina crowns (94.8%) and reinforced glass-ceramic crowns (93.7%), were similar to that (95.6%) for metal-ceramic crowns.

Since all of the reported clinical fractures have occurred over periods of months and years, stress corrosion and slow crack growth may be important variables to consider when analyzing or predicting the time-dependent fracture probability for bilayer ceramic and

metal-ceramic prostheses. Thus, the objective of this study was to apply dynamic fatigue data, finite element analysis of three crown models, and CARES/Life analysis [3], to determine the effect of load orientation and thickness ratio of core ceramic to veneer ceramic on the predicted time-dependent fracture probability for posterior bilayer ceramic crowns that are made with a lithium-disilicate-based glass-ceramic core and its veneering ceramic.

Ceramic-veneered, lithium-disilicate-based core crowns were selected for the current study to characterize the risk for fracture of veneered core ceramics with three thickness ratios of core to veneer ceramic and high-load oblique orientations that simulate extreme bruxism and parafunctional behavior.

2. Materials and methods

2.1. Ceramic specimen preparation

The core ceramic, E2C (Empress 2 lithium-disilicate-based glass-ceramic, Ivoclar Vivadent, Schaan, Liechtenstein) and its veneering ceramic, E2V (Empress 2 Veneering Ceramic, Ivoclar Vivadent), were prepared separately as monolithic bars (Table 1) for four-point flexure testing in five groups of 30 bars each, with dimensions of 28 mm × 4 mm × 1.8 mm. The bars were fractured by dynamic fatigue tests at four stressing rates (0.05 MPa/s, 0.1 MPa/s, 1.0 MPa/s, and 10 MPa/s) in water. One 30-specimen inert strength group was tested at 10 MPa/s in silicone oil. Before testing, each bar was polished through 30 µm alumina abrasive and beveled slightly at a 45° angle along each longitudinal edge to minimize the risk for edge fracture. The load was applied by two steel rollers on the upper central area of each bar, which had a support length of 20 mm.

The flat bars were used to characterize the Weibull parameters for the E2C and E2V materials. The Weibull parameters reflect the characteristic strength, scale parameter, and statistical scatter in strength (Weibull modulus) for a given ceramic. It is standard practice in the ceramic structural reliability literature to obtain these parameters by fracturing simple specimen geometries such as tensile specimens, flexure bars, and C-ring specimens. The ASTM C 1161 test method describes the testing of flexure bars to generate the Weibull parameters for ceramic materials. These parameters were used in the present study to compute the reliability (time-dependent failure probability) of the veneered glass-ceramic crowns.

2.2. Finite element model

Modeling of the bilayer ceramic crowns was performed using ANSYS Finite Element Analysis software (ANSYS, Inc., Canonsburg, PA). The molar crown models were designed with mesiodistal and buccolingual dimensions of 10 mm each, an occlusogingival height of 5 mm, and core/veneer thickness ratios of 0.33 (0.4 mm/1.2 mm), 0.6 (0.6 mm/1.0 mm) (Fig. 1), and 1.0 (0.8 mm/0.8 mm). A distributed load of 500 N was applied over an area of 2 mm² in the central fossa area of the crown models at angles to the horizontal axis of 35°, 70°, and 90°. The refined model was meshed and refined using ANSYS software. The half model of the crown (symmetric section) contained a total of 2,726 three-dimensional 20-node solid elements (SOLID95) and 10,554 nodes. The element breakdown was as follows: 0.4 mm—717 of the core elements and 1,781 of the veneer elements; 0.6 mm—1,048 core elements and 1,450 veneer elements; 0.8 mm—1,392 core elements and 1,106 veneer elements. In all cases 228 elements were used in the supporting epoxy resin die, which simulated tooth dentin.

2.3. CARES/Life analysis

The time-dependent probability of failure was calculated using the CARES/Life software [4] (NASA, NASA Glenn Research Center, Cleveland, OH). This software, which was developed to predict the reliability and life expectancy of structures made from advanced ceramics, glass, intermetallic compounds, and other brittle materials, was linked with the commercially-available finite element analysis package, ANSYS (ANSYS, Inc., Canonsburg, PA).

WeibPar software (Connecticut Reserve Technologies, Gates Mills, OH) was used for Weibull parameter estimates. CARES software (Ceramic Analysis and Reliability Evaluation of Structures, NASA Glenn Research Center, Cleveland, OH) was used for determining the time-dependent fracture probability for the bilayer crowns. For CARES/Life analyses, appropriate Weibull and slow crack growth (SCG) parameters were applied to the ceramics modeled as bilayer crowns in an ANSYS FEA simulation.

3. Results

Shown in Fig. 2 is a plot of the inert flexure strength distribution (fracture probability versus flexure strength) of ceramic E2V that was tested at 10 MPa/s in oil. The flexure strength of ceramic E2V as a function of stressing rate in water is shown in Fig. 3. The mean flexural strength and standard deviation of the two ceramics are 247 ± 74.8 MPa for E2C and 93.9 ± 10.9 MPa for E2V (Table 2). Also listed are the characteristic strength, effective volume (V_e), volume scale parameter (σ_{0V}), effective area (A_e), and the area scale parameter (σ_{0A}). σ_{0V} and σ_{0A} are the Weibull material scale parameters based on volume, V , and area, A , while V_e and A_e are the effective volume and effective area, respectively. The scale parameters are equal to the strength of a unit-size (volume or area) specimen tested in pure tension. The Weibull parameters m and σ_{0i} ($i = V$ or A) are material properties, which are independent of component geometry, loading, and size.

Shown in Fig. 3 is the calculated stress distribution in the E2C/E2V crown model with a core/veneer thickness ratio of 0.33 (0.3 mm/1.2 mm) for a vertical load of 500 N. The greatest tensile stress occurs within the core ceramic (E2C) directly below the site of loading. Note that a relatively low tensile stress of 5 MPa or less is produced in the veneer ceramic below the site of loading in the central fossa region.

The fracture probabilities of E2C/E2V crowns as a function over time of thickness ratio and loading angle under a vertical load of 500 N are shown in Fig. 5. The maximum principal tensile stresses for the E2V and E2C ceramics for the three thickness ratios maximum stress, σ_{max} , are summarized in Table 3.

Table 4 lists the fast-fracture and time dependent fracture probabilities of E2C/E2V ceramic molar crowns for three core/veneer thickness ratios and a load of 500 N applied within the central fossa at an angle of 70 degrees to the horizontal axis. The fracture probabilities of crowns as a function of time and thickness ratios under a load oriented at a 70-degree angle to the horizontal axis is plotted in Fig. 6. The fracture probability of the crowns with a 0.4 mm core thickness increased from 7.0% for vertical loading (Fig. 5) to 12.1% at 10 years compared to loading applied at a 70° angle to the horizontal axis (Fig. 6). However, the failure probabilities at 10 years for the 0.6-mm and 0.8-mm core ceramic thicknesses decreased to 2.6% and 1.4%, respectively, for the 70° load orientation (Fig. 6).

4. Discussion

The change in maximum stress (Table 3) for the three loading angles resulted from the change in effective volume under tension, which altered the reliability of the ceramic

crowns. Thus, this change was associated with reduced stress and a shift in location of $\sigma_{\max}$. The maximum principal tensile stresses of crowns with 0.6-thick and 0.8 mm-thick cores were relatively insensitive to load orientation. The maximum 10-year fracture probabilities of E2C/E2V crowns made with a 0.4-mm-thick core ceramic are associated with a loading angle of 70 degrees from the horizontal axis. These results support previous recommendations to avoid the use of all-ceramic crowns for individuals who exhibit extreme parafunctional behavior.

Lateral components of mastication force are generated by patients with normal occlusion. However, bruxing patients tend to exert greater forces overall [8] and the forces are more concentrated when no food bolus is present as is most often the case during bruxing. These forces are known to cause excessive wear of opposing tooth enamel over time. Maximum biting force (MBF) and tooth wear index scores are significantly higher in bruxers (p values <0.05) compared to non-bruxers [8].

It is obvious that for the stresses applied to the crown, the veneer will control failure since it is weaker and more susceptible to slow crack growth. For the 0.33 thickness ratio (0.4 mm/1.2 mm), the maximum stress in the veneer, $\sigma_{\max}$, is significantly greater for the 70° load orientation case compared with the vertical load case, resulting in a higher P_f as shown in Fig. 6. However, as shown in this figure for the 0.6/1.0 and 0.8/0.8 cases, the P_f for the 70° load orientation case is lower than that when the load is applied vertically (Fig. 5). Table 3 shows a slightly higher stress in the veneer when the load is applied at 70° for the 0.6/1.0 and 0.8/0.8 systems, yet the P_f is lower than for the vertical loading case. The reason for this apparent contradiction is that the volume of material stressed in tension for the vertically-loaded crown is larger than that for the crown loaded at 70 degrees, resulting in a higher probability of fracture.

The increase in core thickness from 0.4 mm to 0.8 mm has a relatively small effect on the maximum principal tensile stress in the ceramic. This result is consistent with the findings in a previous report [9], which suggest that a core thickness above 0.5 mm has little effect on strength of bilayer ceramic crowns.

The probability of fracture over a 10-year period is essentially zero for monolithic lithium-disilicate-based glass-ceramic crowns with a thickness of 1.6 mm under either a vertical or oblique (70°) load of 500 N. This result is consistent with a fracture probability of 0.0026%, which was predicted by CARES software for monolithic lithium-disilicate-based glass-ceramic three-unit bridges that were subjected to an assumed static load of 100 N [10]. This fracture probability of 0.0026% at 10 years is significantly less than the 6% probability for leucite-based glass-ceramic FDPs. However, the applied load of 100 N in that study is quite low compared with the range of clenching forces that are generated on posterior teeth for individuals with a complete dentition (244 to 1243 N) [11].

Ceramic strength data are asymmetrical and always positive. Thus, they are better described using the Weibull distribution than the Gaussian distribution function. To obtain point estimates of the unknown Weibull distribution parameters, well-defined functions are used that incorporate the failure data and specimen geometry. These functions are referred to as estimators. It is desirable that an estimator should be consistent and efficient. In addition, the estimator should produce unique, unbiased estimates of the distribution parameters.

Different types of estimators exist, including moment estimators, least-squares estimators, and maximum likelihood estimators. The maximum likelihood estimators (MLE) are desirable because of the efficiency and ease of its application when censored failure populations are encountered. Censored data analysis is used when distinct multiple flaw

populations (such as inclusions, pores, and surface flaws) exist in the strength data. The MLE method also provides a methodology and likelihood ratio bounds (ring), to estimate the confidence bounds for the Weibull parameters. In addition, the MLE approach can seamlessly be used to eliminate the bias of the estimated Weibull parameters.

If an estimator yields biased results, the value of the individual estimates can be corrected if the estimators are invariant. The bias associated with the estimate of the characteristic strength is minimal (<0.3% for 20 test specimens compared with a ~0.7% bias for the same number of specimens. This bias is usually ignored. However, the WeibPar program allows for the unbiasing of the Weibull modulus and the Weibull characteristic strength. Statistical bias is associated with the maximum likelihood estimators, which can always be reduced by increasing the sample size.

The effective volume and area for a given loaded component, V_e and A_e , respectively, represent the equivalent volume or area of a tensile specimen subjected to uniform tension that is equal to the maximum stress in the component that would result in the same failure probability. Under multiaxial loading conditions, the effective stress in the component is computed by the CARES/Life code according to a fracture criterion and crack shape selected by the user. The effective sizes are used with characteristic strength to compute the scale parameters. The normalized material scale parameters are then used in CARES/Life to compute the probability of fracture for the bilayer ceramic crowns.

5. Conclusions

A decrease in the core ceramic thickness from 0.8 to 0.4 mm doubles the predicted fracture probability at 1, 5, and 10 years for vertically loaded crowns. Changing the load orientation from 90° to 70° increases the 10-year fracture probability by 79.4% for crowns with a 0.4-mm-thick core ceramic. For the 0.8 and 0.6-mm-thick core models, the maximum tensile stress ($\sigma_{\max}$) in the E2C ceramic is lower for the 70° case compared with the vertical loading case. $\sigma_{\max}$ changes in location from the base surface of the core layer for the vertical loading case to the base of the veneer layer for the 70° loading case.

This study was based on several simplifying assumptions including perfect bonding of the crowns to the substructure, a typical distribution of processing flaws, and a negligible effect of residual thermal contraction mismatches between the veneering and core ceramic. The susceptibility for chipping fracture of all-ceramic crowns is greater than that for metal-ceramic crowns [11].

Because of the lack of standardized methods for describing clinical chipping fractures, materials scientists are limited in their ability to predict such outcomes from in vitro data [1,2]. In addition, none of the clinical reports on veneered E2C crowns provided precise core/veneer thickness ratios for each crown, so relationships between crown design and clinical performance cannot be analyzed. In future clinical trials that are focused on performance and survival analysis of ceramic-base prostheses, it is essential to record specific design dimensions and information on potential parafunctional effects.

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Fig. 1.

Finite element model of a bilayer crown with a core ceramic thickness (aqua) of 0.6 mm and a veneer thickness (purple) of 1.0 mm. The vertical load of 500 N (red arrows) was distributed along a 2 mm² area in the central fossa. The red area immediately below the crown represents dentin.

Fig. 2.
Inert flexure strength distribution for E2V ceramic tested at 10 MPa/s in oil.

Fig. 3.
Flexure strength versus stressing rate for E2V ceramic tested in water.

Fig. 4. Stress distribution patterns in the mid-section of the occlusal region (top left, top right, and lower left) and the interproximal region (lower right) of an E2C/E2V molar crown with a core/veneer thickness ratio of 0.33 (0.4 mm/1.2 mm) that was subjected to a distributed vertical load of 500 N in the central fossa area.

Fig. 5. Time-dependent probability of fracture as a function of core/veneer thickness ratio for 1.6-mm-thick E2C/E2V molar crowns resulting from a distributed 500 N vertical load in the central fossa.

Fig. 6. Time-dependent probability of fracture as a function of core/veneer thickness ratio for 1.6-mm-thick E2C/E2V molar crowns resulting from a distributed 500 N load applied at an angle of 70° to the horizontal axis.

Table 1

Sample size and treatment conditions used for preparation of ceramic specimens.

Ceramic	Total number of specimens	Processing Temperature (°C)	Ground through 30 µm abrasive	Beveled edges (45 µm)	Additional firings per ISO 6872
E2V	150	800	150	150	2 each
E2C	150	920 (HIP)*	150	150	3 each

Table 2

Weibull parameters for E2C and E2V ceramics tested under inert conditions.

Parameter estimation method	Mean strength (MPa)	Weibull modulus	Characteristic strength σ_0 (MPa)	Effective volume V_e (mm ³)	Volume scale parameter σ_{0V} (MPa mm ^{3/m})	Effective area A_e (mm ²)	Area scale parameter σ_{0A} (MPa mm ^{2/m})
E2C Linear regression	246.6± 47.8	6.3	265	3.13	317	27.0	446
E2C Maximum Likelihood	246.6 ± 47.8	5.3 (4.2–6.8)	266 (251–282)	3.75	341	28.2	498
E2V Linear regression	93.9 ± 10.9	10.5	98.5	2.4	107.2	32.5	136.0
E2V Maximum Likelihood	93.9 ± 10.9	9.0 (7.1–11.5)	98.7 (95.2–102)	2.9	111.1	33.5	145.9

Maximum tensile stress, $\sigma_{\max}$ (MPa), as a function of core/veneer thickness ratio and loading angles of 35°, 70°, and 90° to the horizontal axis.

Table 3

Core/Veneer Thickness Ratio (mm/mm)	Ceramic						
	E2V			E2C			
	Load Orientation Relative to Horizontal Axis						
	90°	70°	35°	90°	70°	35°	
	$\sigma_{\max}$ (MPa)						
0.33 (0.4 mm/1.2 mm)	31.5	43.5	166.4	53.3	37.7	65.0	
	30.8	33.8	166.7	53.0	31.0	57.9	
1.0 (0.8 mm/0.8 mm)	29.5	31.5	166.6	52.6	34.5	69.2	

Table 4

Fast-fracture and time dependent fracture probability of E2C/E2V ceramic molar crowns for three core/veneer thickness ratios and a load of 500 N applied within the central fossa at an angle of 70 degrees to the horizontal axis.

Time	Core/Veneer Thickness Ratio (mm/mm)		
	0.33 (0.4 mm/1.2 mm)	0.6 (0.6 mm/1.0 mm)	1.0 (0.8 mm/0.8 mm)
	Probability of Fracture (%)		
Time 0 (fast fracture)	1.26×10^{-5}	7.87×10^{-6}	8.73×10^{-6}
1 hour	6.8×10^{-2}	1.34×10^{-2}	6.63×10^{-3}
10 hour	0.197	3.84×10^{-2}	1.88×10^{-2}
1 day	0.295	5.75×10^{-2}	2.80×10^{-2}
10 day	0.852	0.166	8.02×10^{-2}
1 month	1.41	0.275	0.133
1 year	4.40	0.866	0.419
5 years	9.00	1.81	0.878
10 years	12.2	2.49	1.20