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H. Lekesiz[1]*

[1]Bursa Technical University, Department of Mechanical Engineering, Gaziakdemir Mah. Mudanya Cad. No: 4/10 Osmangazi, Bursa, Turkey; *corresponding author, huseyin.lekesiz@btu.edu.tr

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Reliability Estimation for Single-unit Ceramic Crown Restorations

ABSTRACT

The objective of this study was to evaluate the potential of a survival prediction method for the assessment of ceramic dental restorations. For this purpose, fast-fracture and fatigue reliabilities for 2 bilayer (metal ceramic alloy core veneered with fluorapatite leucite glass-ceramic, d.Sign/d.Sign-67, by Ivoclar; glass-infiltrated alumina core veneered with feldspathic porcelain, VM7/In-Ceram Alumina, by Vita) and 3 monolithic (leucite-reinforced glass-ceramic, Empress, and ProCAD, by Ivoclar; lithium-disilicate glass-ceramic, Empress 2, by Ivoclar) single posterior crown restorations were predicted, and fatigue predictions were compared with the long-term clinical data presented in the literature. Both perfectly bonded and completely debonded cases were analyzed for evaluation of the influence of the adhesive/restoration bonding quality on estimations. Material constants and stress distributions required for predictions were calculated from biaxial tests and finite element analysis, respectively. Based on the predictions, In-Ceram Alumina presents the best fast-fracture resistance, and ProCAD presents a comparable resistance for perfect bonding; however, ProCAD shows a significant reduction of resistance in case of complete debonding. Nevertheless, it is still better than Empress and comparable with Empress 2. In-Ceram Alumina and d.Sign have the highest long-term reliability, with almost 100% survivability even after 10 years. When compared with clinical failure rates reported in the literature, predictions show a promising match with clinical data, and this indicates the soundness of the settings used in the proposed predictions.

KEY WORDS: finite element analysis (FEA), restorative materials, statistics, stress analysis, CAD, biomechanics.

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INTRODUCTION

All-ceramic restorations present an excellent esthetic appearance along with superior biocompatibility. However, ceramics are brittle and vulnerable to fatigue fracture because of repetitive chewing motion (Morena *et al.*, 1986). There are several types of cracks that can be detected in experimental simulations, and different cracks can participate in failure in static and fatigue loadings (Zhang *et al.*, 2013). Some of the fracture modes seen in those experiments cannot be easily interpreted from fractographic analysis of failed crowns, but radial cracks emanating from the core adhesive interface are known to lead to the bulk failures that are seen in most clinical practices (Kelly, 1999).

A statistical approach is necessary to predict the reliability of dental ceramics, due to widely scattered failure loads, which result from wide distribution in both the size and orientation of initial microscopic flaws. Statistical models (Weibull, 1939; Batdorf and Crose, 1974) have led to significant improvements in survivability estimations for dental ceramics.

In this study, fast-fracture and long-term (fatigue) reliabilities of 5 different bilayer and monolithic single posterior ceramic crown restorations were predicted based on a probabilistic method (Nemeth *et al.*, 2003). Interfacial radial cracks were considered for predictions, and both perfectly bonded and completely debonded cases were considered to understand the influence of adhesive/restoration bonding quality on reliability. Long-term failure predictions were compared with clinical data presented in the literature. Veneered and monolithic restorations, metal-ceramic, and all-ceramic restorations were compared, and the potential of the prediction method was evaluated for possible future investigations. This assessment is particularly important for the dental industry because there is no standard approach to evaluation of the reliability of actual ceramic restorations in the literature.

MATERIALS & METHODS

Fast-fracture and long-term failure probabilities of mandibular first molar crown restorations were predicted theoretically by the method outlined in Fig. 1 (Nemeth *et al.*, 2003). Five restorations with 6 different ceramics were considered in the calculations: a porcelain-fused-to-metal (PFM) restoration (palladium-silver ceramic alloy core veneered with fluorapatite leucite glass-ceramic, d.Sign/d.Sign-67, by Ivoclar Vivadent, Schaan, Liechtenstein); a full-ceramic restoration (glass-infiltrated alumina core veneered with feldspathic porcelain, VM7/In-Ceram Alumina, by Vita Zahnfabrik, Bad Säckingen, Germany); and 3 monolithic restorations (leucite-reinforced glass-ceramic, Empress and ProCAD, lithium-disilicate glass-ceramics, Empress 2, all by Ivoclar Vivadent). The study was limited to the materials listed above, because the required material properties, obtained by the same experimental method as for the materials in this study, are not yet available for newer materials. Some of the materials used in this study have been reformulated and

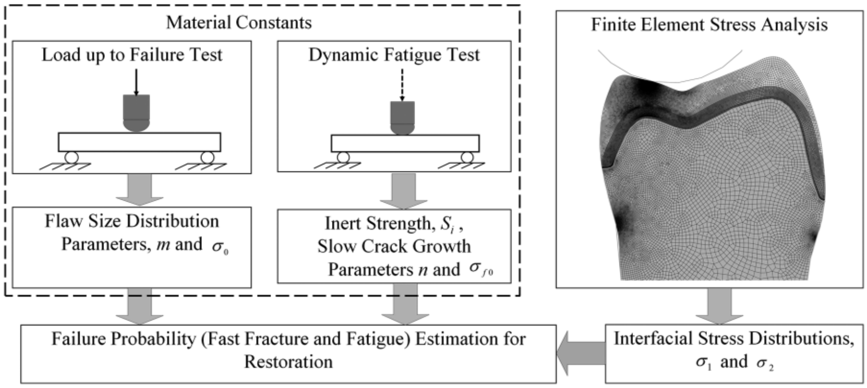


Figure 1. Theoretical method to predict failure probability for fast fracture and fatigue loadings.

therefore are listed with their new names, as follows: IPS Empress Esthetic for Empress, IPS e.max Press for Empress 2, and IPS Empress CAD for ProCAD. These reformulations have optimized the physical properties based on experience with the older versions and newer manufacturing techniques. However, either clinical studies on these new materials are not available or the materials have been evaluated for only a very short period in the literature.

There are 7 main inputs for the predictions (Fig. 1): flaw size distribution parameters, m and σ_0; inert strength, S_i; slow crack growth parameters, n and σ_{f0}; and interfacial stresses in principal directions, σ_1 and σ_2 . All these inputs were inserted into the following failure probability formula (Nemeth *et al.*, 2003), as functions of time, t:

$$P_f\left(t\right)=1-\mathbf{exp}\left[-\frac{{\sigma_0}^{-m}}{\pi}\int\limits_A\int\limits_0^{\pi}\left\{\frac{\left(n+1\right)\cdot {S_i}^{n-2}\cdot g\cdot\sigma_{Ieq}^{n}}{{\sigma_{f0}}^{n+1}}\cdot t+\sigma_{Ieq}^{n-2}\right\}^{\frac{m}{n-2}}d\alpha\, dA\right]$$

where g is the factor depending on the loading profile of a chewing cycle, and σ_{Ieq} is the equivalent stress obtained from interfacial stress components. Here, α represents the angle between a crack normal and principal direction, and A represents the surface area at the interface. Equivalent stress was obtained based on the critical strain energy release rate criterion written for Griffith cracks. The loading factor g is calculated for a sinusoidal chewing cycle with 400 N maximum and 40 N minimum biting forces. A frequency of 1 Hz and 1.5 million chewing cycles a year were anticipated (Gratton *et al*., 2001). The integrals in the equation were evaluated numerically with Matlab (Version 8.3, The MathWorks Inc., Natick, MA, USA).

Material Constants

In this study, m and σ_0 were obtained from biaxial piston-on-three-ball tests as reported in Gonzaga *et al.* (2011) for all materials except ProCAD. The Weibull statistics model was used in the aforementioned study. However, a more sensible physics-based statistical approach (Batdorf and Crose, 1974) was utilized in the calculations in this study, and therefore, an additional calculation was conducted for the conversion of σ_0 values.

Slow crack growth parameters, n and σ_{f0}, and inert strength values for all ceramics except ProCAD were obtained directly from Gonzaga *et al.* (2011), and for ProCAD the data were obtained from biaxial ball-on-ring tests (Lekesiz *et al.*, 2009). All material constants are listed in Table 1.

Finite Element Model

A 2-D finite element model was developed in Abaqus CAE (Release 6.12, Dassault Systèmes, Yvelines, France) to determine interfacial stress components. The geometry of the model was created by the assembly of 5 different layers: dentin, cement, core, veneer, and a rigid ball. The outline shape of the layers was obtained from a CAD model of a scanned mandibular first molar tooth. The 2-D plane strain model with 10 mm out-of-plane thickness was created from the middle section of the scanned model positioned in the distal aspect. The section had the following thicknesses: minimum 1 mm for veneer, 0.5 mm for core, and uniform 0.1 mm for cement layers. The height of the restored crown was 6.6 mm at the buccal side, 4.3 mm at the lingual side, with 10.5 mm bucco-lingual width and 14 mm root length. A rigid ball with 9-mm diameter was placed on top of the tooth touching the lingual part of the occlusal cusps, where it created a more critical stress state compared with that created by buccal and middle contacts.

Elastic material constants used in the finite element model are listed in Table 1. A frictionless, surface-to-surface contact was defined between the rigid ball and occlusal surfaces to simulate the tooth and food contact in chewing. To analyze the influence of possible debondings at the interface between dentin and core, a completely debonded model was also defined by creation of a frictionless contact between adhesive and core layers.

For boundary conditions, the root of the dentin was fixed in all directions, and the rigid ball was restricted to movement in a horizontal direction. The biting force (P), varying from 200 N to 1,200 N, was applied to the ball center in a vertical direction.

The 2-D model was meshed with plane-strain linear quad and triangular elements, with a quad-dominated mesh algorithm. An adaptive meshing option was used to mesh the entire structure, and a very fine mesh was generated, which led to a total number of 92,851 elements.

RESULTS

The contours of maximum principal stress for In-Ceram Alumina core and monolithic ProCAD (P = 1,000 N) are shown in Figs. 2a and 2b, respectively. As can be seen, maximum tensile stress occurred at the adhesive interface for both In-Ceram Al core and monolithic ProCAD, and this was true for all restoration materials considered in this study.

For assessment of the fast-fracture reliability of restorations, failure probabilities are plotted in Figs. 2c and 2d as a function of load, for perfectly bonded and completely debonded cases,

Table 1. Material Parameters Used in the Finite Element and Probability Calculations

	Mechanical Properties		Flaw Size Distribution Parameters		Slow Crack Growth Parameters	
	Elastic Modulus, E (GPa)	Poisson's Ratio, ν	Characteristic Strength, σ_0 (MPa)	Weibull Modulus, *m*	Fatigue Parameter, *n*	Scaling Parameter, σ_{f0} (MPa)
VM7	66.7(1)	0.215(2)	81.44(8)	5.2(2)	26.3(2)	70.55(2)
d.Sign	36(3)	0.217(2)	45.90(8)	11.7(2)	20.4(2)	47.99(2)
Empress	67(4)	0.21(2)	99.05(8)	9.4(2)	30.1(2)	100.45(2)
Empress 2	104(4)	0.225(2)	179.21(8)	9.5(2)	17.2(2)	184.71(2)
ProCAD	62(5)	0.25(5)	200.09(7)	5.92(5)	24.13(7)	139.76(7)
In-Ceram	270(5)	0.239(2)	375.48(8)	11.2(2)	31.1(2)	384.22(2)
Dentin	16(6)	0.31(6)				
Resin	8(6)	0.33(6)				

(1) Borba *et al.* (2011), (2) Gonzaga *et al.* (2011), (3) Kontonosaki *et al.* (2008), (4) Rekow and Thompson (2007), (5) Wang *et al.* (2007), (6) Rekow *et al.* (2006), and (7) Lekesiz *et al.* (2009). (8) Calculated in this study based on the values provided in Gonzaga *et al.* (2011).

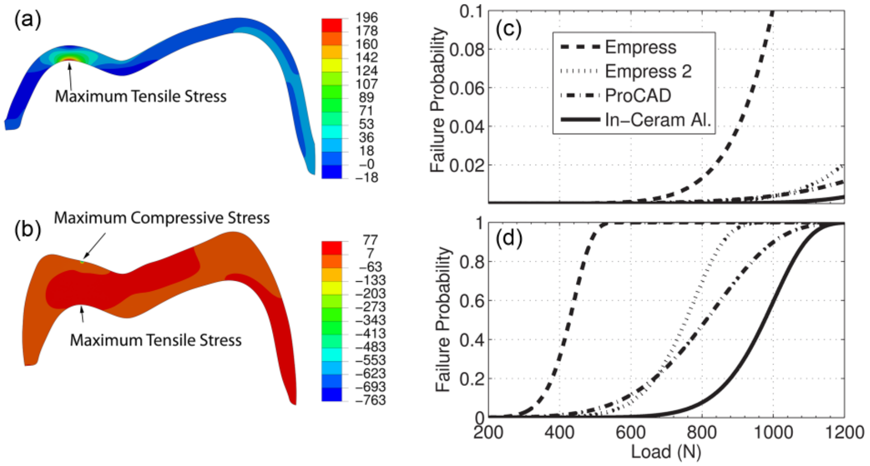


Figure 2. Contours of maximum principal stress for In-Ceram Alumina core and monolithic ProCAD and failure probabilities at the crown-dentin interface for perfectly bonded and completely debonded cases. **(a)** Contours of maximum in-plane principal stress for In-Ceram Alumina Core (P = 1,000 N). **(b)** Contours of maximum in-plane principal stress for monolithic ProCAD (P = 1,000 N). **(c)** The failure probability at the crown-dentin interface (Empress, Empress II, ProCAD, and In-Ceram Al) under lingual loading as a function of chewing loading for a perfectly bonded case. **(d)** The failure probability at the crown-dentin interface (Empress, Empress II, ProCAD, and In-Ceram Al) under lingual loading as a function of chewing loading for a completely debonded case.

respectively. Veneer materials are excluded in this graph because they exhibit very small failure probability.

For the perfectly bonded case, In-Ceram Alumina showed the lowest failure probability. Empress showed the highest failure probability. Empress 2 and ProCAD showed similar failure probabilities, and they had a much lower failure probability compared with Empress and were closer to In-Ceram Alumina. For the completely debonded case, all materials showed a significant increase in failure probability. In the loading range of 0 to 1,200 N, all materials failed completely. This significant change indicates how critically the reliability depends on bond quality. ProCAD showed the most dramatic increase, and Empress, Empress 2, and In-Ceram Al shifted toward the left, which indicates a magnitude change rather than a shape change in the values.

In Fig. 3, the long-term failure probabilities of restorations are plotted for 5 and 10 years. The failure rate for a debonded case at the five-year period is also shown in the graph, to aid in our understanding of the influence of debonding in fatigue loading. In case of perfect bonding, both veneer materials, VM7 and d.Sign, had very small failure probability, in the order of 10^{-4} and 10^{-6}, respectively. In-Ceram Alumina showed failure probability in the order of 10^{-6}, even after 10 years. Among monolithic restorations, ProCAD showed the least failure probability, with a maximum $4.7\ (10)^{-4}$ failure rate, and Empress showed the highest rate, with approximately 7% failure rate for 10 years. Empress 2 had much lower failure probability compared with Empress, with a 1.7% failure rate for 10 years.

For completely debonded restorations in a five-year period, d.Sign failed almost completely (96%), while for VM7 and In-Ceram Al, failure rates reached 2.5% and 1.4%, respectively. For monolithic restorations, Empress and Empress 2 failed completely, while ProCAD had a 37% failure rate.

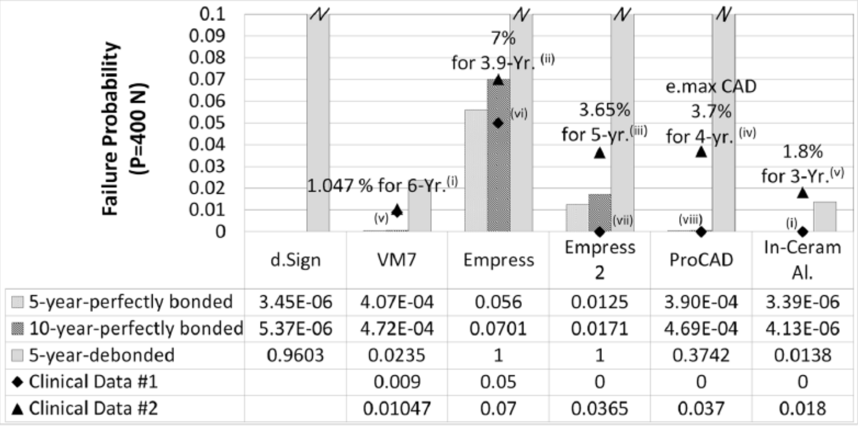
Two groups of clinical data for all materials except d.Sign are shown in Fig. 3. All the clinical studies cited in this paper were scanned to obtain failure rates for posterior teeth. In addition, only fracture data were considered, and non-mechanical failures were eliminated. For ProCAD, data for a full-contour monolithic crown were not available in the literature, and therefore data for e.max CAD are presented in the graphs for comparison of CAD restorations. Details of the clinical data can be found in Table 2.

DISCUSSION

Based on Fig. 3, PFM represented better long-term reliability compared with In-Ceram Alumina veneered with VM7; however,

Table 2. Details of the Clinical Data Used in Figure 3

Material	Source	Fracture Rates	Time Interval, yr	Location
In-Ceram Al.	McLaren and White (2000)	1.8%	3	Posterior (no statistically significant difference between posterior and anterior crowns)
	Segal (2001)	0% (0 out of 191)	6	Molar
VM7	McLaren and White (2000)	0.9%	3	Posterior (no statistically significant difference between posterior and anterior crowns)
	Segal (2001)	1.047% (2 out of 191)	6	Molar
Empress	Sjögren *et al.* (1999)	7%	3.9	Molar
	Fradeani and Aquilano (1997)	5%	6	Posterior (no statistically significant difference between posterior and anterior crowns)
Empress 2	Mansour *et al.* (2008)	3.65%	5	Posterior (no statistically significant difference between posterior and anterior crowns)
	Marquardt and Strub (2006)	0%	5	Posterior
e.max CAD (compared with ProCAD)	Reich and Schierz (2013)	3.7% (1 out of 41)	4	Posterior
	Fasbinder *et al.* (2010)	0%	2	Posterior



	d.Sign	VM7	Empress	Empress 2	ProCAD	In-Ceram Al.
▢ 5-year-perfectly bonded	3.45E-06	4.07E-04	0.056	0.0125	3.90E-04	3.39E-06
▨ 10-year-perfectly bonded	5.37E-06	4.72E-04	0.0701	0.0171	4.69E-04	4.13E-06
▢ 5-year-debonded	0.9603	0.0235	1	1	0.3742	0.0138
◆ Clinical Data #1		0.009	0.05	0	0	0
▲ Clinical Data #2		0.01047	0.07	0.0365	0.037	0.018

(i)Segal (2001), (ii)Sjogren et al. (1999), (iii) Mansour et al. (2008), (iv)Reich and Schierz (2013), (v) Mclaren and White (2000) (vi)Fredani and Aquilano (1997), (vii) Marquadart and Strub (2006), (viii) Fasbinder et al. (2010)

Figure 3. Failure probability of veneer and core materials after 5 and 10 years for a perfectly bonded case and after 5 years for a completely debonded case compared with 2 sets of clinical failure rates presented in the literature (higher predictions are indicated by triangular dots, and lower predictions are indicated by diamonds).

they both showed minor failure rates (10^{-6} and 10^{-4}). Reliability of both PFM and VM7/In-Ceram Al restorations was determined by the veneer material, because core materials have extremely small failure probability. When bilayer and monolithic restorations were compared, ProCAD had reliability similar to that of VM7/In-Ceram Al.

When compared with some reported clinical failure rates, it can be stated that the theoretical predictions showed relevant quantitative values for some materials. For instance, Pröbster (1993) and Segal (2001) reported zero failure for posterior In-Ceram Alumina crown cores, and this matches the prediction. For Empress, Fradeani and Aquilano (1997) reported 5% posterior fracture rate in a six-year period, whereas a 5.6% failure rate was predicted for 5 years in this study. Fasbinder *et al*. (2010) reported a zero fracture rate at 2 years for e. max CAD, while the theoretical predictions were in the order of 10^{-4}. Some predictions did not match well with clinical studies, such as that of Marquardt and Strub (2006), who assessed zero failure for Empress 2, while 1.25% failure was predicted in this study for 5 years. Conversely, Mansour *et al.* (2008) obtained a 3.65% fracture rate for Empress 2 for the same period.

A prediction that matches well with all clinical data is not feasible; however, the order of the failure probabilities for different materials can be predicted well, along with reasonable quantitative values. Differences between predictions and clinical data can be attributed to some factors explained below.

As presented in Figs. 2 and 3, initial debonding, as a result of inevitable deficiencies at the bonding surface, significantly degrades reliability in either fast-fracture or fatigue loadings. These debondings can be caused by problems either in crown placement, such as surface contaminations, or loss of adhesion in service as a result of natural factors such as thinning of the hybrid layer (Bindl *et al.*, 2005). A complete debonding model determines the low end of reliability, and perfect bonding determines the upper end; however, a model for a more realistic, partial debonding case is not available in the literature. Other than possible debonding, it is anticipated that the following factors may lead to differences between predictions and clinical data, especially those with higher probabilities.

Predictions are conducted assuming a smooth sinusoidal mastication loading throughout the life of the crown. However, a sharp biting force can be applied instantaneously, and this may significantly increase the failure probability. For instance, an abrupt 1,000-N biting force leads to 0.04% failure probability for In-Ceram Alumina, and this is 100 times more compared with failure probability for 5 years.

Surface treatments significantly influence the failure probability of dental ceramics. For instance, sandblasted and ground Empress I and II showed lower Weibull modulus values compared with untreated and polished ones (Albakry *et al*., 2004). Etching also leads to a better reliability by increasing the bonding strength in crown restorations (Blatz *et al*., 2003). Therefore, any difference in surface treatment between 2 studies may lead to significant differences in survivability predictions. Although surfaces are conditioned as in the clinical applications, a perfectly analogous surface with clinical data cannot be expected when material parameters are determined.

In addition to the mechanical factors mentioned above, some deficiencies in the model explained below can also yield differences, but these are anticipated to be minor. A 2-D model was utilized in the calculations rather than a 3-D model. In this 2-D model, it was impossible to incorporate some factors such as the interproximal wall height differences, which influence stress distribution (Coelho *et al.*, 2009). However, a proper tooth model involving all these factors requires a significant increase in both design and analysis times. Convergent results for both stress and failure probability calculations became computationally costly for the 140 different analyses (28 different loads for all restorations) run in this study. Besides the need for using significant quantities of 3-D elements, the choice of element type was reduced to only the tetragonal element, due to complexity of the actual tooth shape. While a good representation of shape can be gained, accuracy may be sacrificed with the 3-D model because of these limitations (Romeed *et al*., 2006). The 2-D model used in this study is a good representation of actual tooth shape, because both loading and geometry were similar throughout the sections in the distal aspect (Benazzi *et al.*, 2012), and, more importantly, it leads to a more conservative estimation. Potential improvement with a 3-D model is not expected to be sufficient to explain differences between clinical data and predictions, because a 3-D model may require more approximations in the stage of probability calculations taking place after finite element analysis.

Specific to the ProCAD, a different experimental set-up was utilized for determining material constants, where ball-on-ring tests were conducted under water. For other materials, piston-on-three-ball tests under artificial saliva were used by Gonzaga *et al*. (2011). However, piston-on-three-ball and ball-on-ring tests showed almost identical stress distributions in cases of frictionless contact between supporting ring and disc (Huang and Hsueh, 2011), and water and saliva are not expected to lead to significantly different fatigue parameters (Morena *et al*., 1986). Thus, differences in test methods are not anticipated to create a noticeable difference in predictions.

In conclusion, one can predict the lifetime of a single ceramic crown with a reasonably good approximation by the proposed method. Based on predictions, it can be stated that PFM shows superior reliability compared with all-ceramic bilayer restorations unless debonding occurs, and In-Ceram Alumina and VM7 offer comparable reliability plus better resistance in cases of debonding. Monolithic restorations are extremely sensitive to debonding, but ProCAD presents a comparable reliability with In-Ceram Al in cases of perfect bonding. Even though there are some differences in assumptions between clinical and theoretical models, differences can be justified and an even more accurate prediction tool for single crowns may be developed by incorporating better mechanical models in the future.

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REFERENCES

Albakry M, Guazzato M, Swain MV (2004). Effect of sandblasting, grinding, polishing and glazing on the flexural strength of two pressable all-ceramic dental materials. *J Dent* 32:91-99.

Batdorf SB, Crose JG (1974). A statistical theory for the fracture of brittle structures subjected to nonuniform polyaxial stresses. *J Appl Mech* 41:459-464.

Benazzi S, Kullmer O, Grosse I, Weber GW (2012). Brief communication: comparing loading scenarios in lower first molar supporting bone structure using 3D finite element analysis. *Am J Phys Anthropol* 147:128-134.

Bindl A, Richter B, Mörmann WH (2005). Survival of ceramic computer-aided design/manufacturing crowns bonded to preparations with reduced macroretention geometry. *Int J Prosthodont* 18:219-224.

Blatz MB, Sadan A, Kern M (2003). Resin-ceramic bonding: a review of the literature. *J Prosthet Dent* 89:268-274.

Borba M, de Araújo MD, de Lima E, Yoshimura HN, Cesar PF, Griggs JA, *et al*. (2011). Flexural strength and failure modes of layered ceramic structures. *Dent Mater* 27:1259-1266.

Coelho PG, Silva NR, Thompson VP, Rekow D, Zhang G (2009). Effect of proximal wall height on all-ceramic crown core stress distribution: a finite element analysis study. *Int J Prosthodont* 22:78-86.

Fasbinder DC, Dennison CB, Heys D, Neiva G (2010). A clinical evaluation of chairside lithium disilicate CAD/CAM crowns. *J Am Dent Assoc* 141(Suppl 2):10S-14S.

Fradeani M, Aquilano A (1997). Clinical experience with empress crowns. *Int J Prosthodont* 10:241-247.

Gonzaga CC, Cesar PF, Miranda WG Jr, Yoshimura HN (2011). Slow crack growth and reliability of dental ceramics. *Dent Mater* 27:394-406.

Gratton DG, Aquilino SA, Stanford CM (2001). Micromotion and dynamic fatigue properties of the dental implant-abutment interface. *J Prosthet Dent* 85:47-52.

Huang CW, Hsueh CH (2011). Piston-on-three-ball versus piston-on-ring in evaluating the biaxial strength of dental ceramics. *Dent Mater* 27:e117-e123.

Kelly JR (1999). Clinically relevant approach to failure testing of all-ceramic restorations. *J Prosthet Dent* 81:652-661.

Kontonasaki E, Kantiranis N, Papadopoulou L, Chatzistavrou X, Kavouras P, Zorba T, *et al*. (2008). Microstructural characterization and comparative evaluation of physical, mechanical and biological properties of three ceramics for metal-ceramic restorations. *Dent Mater* 24:1362-1373.

Lekesiz H, Katsube N, Rokhlin S, Seghi R (2009). Probabilistic lifetime prediction tools for fatigued bonded ceramic restorations. *J Dent Res* 88(Spec Iss A): Abstract #161. URL accessed on 6/30/2014 at: https://iadr.confex.com/iadr/2009miami/webprogram/Paper120620.html.

Mansour YF, AL-Omiri MK, Khader YS, Al-Wahadni AM (2008). Clinical performance of IPS-Empress 2 ceramic crowns inserted by general dental practitioners. *J Contemp Dent Pract* 9:9-16.

Marquardt P, Strub JR (2006). Survival rates of IPS Empress 2 all-ceramic crowns and fixed partial dentures: results of a 5-year prospective clinical study. *Quintessence Int* 37:253-259.

McLaren EA, White SN (2000). Survival of In-Ceram crowns in a private practice: a prospective clinical trial. *J Prosthet Dent* 83:216-222.

Morena R, Beaudreau GM, Lockwood PE, Evans AL, Fairhurst CW (1986). Fatigue of dental ceramics in a simulated oral environment. *J Dent Res* 65:993-997.

Nemeth NN, Powers LM, Janosik LA, Gyekenyesi JP (2003). CARES/LIFE Ceramics analysis and reliability evaluations of structures life prediction program. Technical Memorandum No: NASA-TM-2003-106316. Cleveland, OH: Glenn Research Center.

Pröbster L (1993). Survival rate of In-Ceram restorations. *Int J Prosthodont* 6:259-263.

Reich S, Schierz O (2013). Chair-side generated posterior lithium disilicate crowns after 4 years. *Clin Oral Invest* 17:1765-1772.

Rekow ED, Harsono M, Janal M, Thompson VP, Zhang G (2006). Factorial analysis of variables influencing stress in all-ceramic crowns. *Dent Mater* 22:125-132.

Rekow ED, Thompson VP (2007). Engineering long term clinical success of advanced ceramic prostheses. *J Mater Sci Mater Med* 18:47-56.

Romeed SA, Fok SL, Wilson NH (2006). A comparison of 2D and 3D finite element analysis of a restored tooth. *J Oral Rehabil* 33:209-215.

Segal BS (2001). Retrospective assessment of 546 all-ceramic anterior and posterior crowns in a general practice. *J Prosthet Dent* 85:544-550.

Sjögren G, Lantto R, Granberg A, Sundström BO, Tillberg A (1999). Clinical examination of leucite-reinforced glass-ceramic crowns (Empress) in general practice: a retrospective study. *Int J Prosthodont* 12:122-128.

Wang Y, Katsube N, Seghi RR, Rokhlin SI (2007). Statistical failure analysis of adhesive resin cement bonded dental ceramics. *Eng Fracture Mech* 74:1838-1856.

Weibull W (1939). A statistical theory of the strength of materials. Handlingar 151: Ingeniörs Vetenskaps Akademien. URL accessed on 6/30/2014 at: http://www.barringer1.com/wa_files/Weibull-1939-Strength-of-Materials.pdf.

Zhang Y, Sailer I, Lawn BR (2013). Fatigue of dental ceramics. *J Dent* 41:1135-1147.