Fatigue of full crown monolithic CAD/CAM restorations for posterior teeth

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Research Article

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Abstract

Objective

The purpose of this study is to estimate the fatigue life of five polycrystalline zirconia CAD/CAM ceramic materials used for posterior restoration. This study presents the first time methodology to translate raw data obtained from laboratory test into useful data to predict the clinical life of dental restoration.

Methods

A typical model for the first molar restored crown is built and transferred into finite element software ANSYS 18.1 flor execution FEA. The materials are: two Y-TZP zirconia (LAVA (LVs), and EVEREST (KVs); IPS e.max CAD; Suprinity PC; and Celtra Duo. Two types of loads are applied, axial load and axial load followed by the sliding motion of lower jaw. The fatigue resistance of various restorative materials is determined.

Results

Experimental findings show that all the samples have fractured between cusps at the same location, which is slightly off the symmetry fissure plane. For crowns made of LAVA and EVEREST, the life is longer than 10 years under an axial load of 1000 N, while the lives for IPS e.max CAD; Suprinity PC; and Celtra Duo were longer than 10 years under an axial load of 185 N. The life of all-ceramic crown materials was predicted by FEA and found to conform to previous experimental and clinical observations.

Conclusion

Crowns made of Y-TZP zirconia has superior fatigue resistance compared to other ceramic CAD/CAM materials.

1. Introduction

Monolithic ceramic restorations made by CAD/ CAM systems have been widely used recently [1]. Among a large number of desired properties, the ability for the materials to endure cyclic loading for a long time (fatigue resistance) is considered the key desired properties for successful restorative materials. Serious concerns have been reported regarding the degradation of ceramic restoration in the oral environment due to a long period under cyclic stresses. Most of the reported failures are observed when ceramic restorations are placed on the posterior [2–4].

Zirconia is found to be an attractive option for restorations among the developed CAD/CAM ceramics due to biocompatibility and high flexural strength. The superior esthetic properties and color stability of lithium disilicate (LD) are excellent [5]. Its lower strength levels, on the other hand, prevented its use for posterior teeth. Moreover, it is vulnerable to fracture due to its fragility [7]. ZLS is recently developed as an alternative to LD and is classified as a glass-ceramic reinforced by lithium silicate and zirconia crystals within its glassy matrix. Studies have reported a better than or similar performance to LD.

The survival of the restorative materials depends primarily on the resistance of the restorative materials to fatigue load, the magnitude and shape of loads, the thickness of the restoration, the surface roughness, and the cement material's shear strength. Despite the fact that fatigue failure is the main cause of fatigue failure, only a few studies have conducted fatigue analysis for restored teeth [8–10], while a large number of studies have focused on static analysis only[9, 11]. The findings obtained from static studies do not have clear useful results for clinical applications and lifetime predictions. Wendler et al. [10] confirmed the fact that the prediction of long-term performance in the oral environment of dental restorative materials should be based on fatigue rather than static strength results. The fatigue output of monolithic crowns developed from glass or polycrystalline CAD-CAM ceramic systems adhesively lubricated with a dentin analog was recently assessed by Alves et al. [11]. They found that CAD-CAM monolithic crowns of Trans YZ show the best fatigue performance. In addition, ZLS crowns also showed better performance than LD crowns. The only limitation of their study is that they used highly simplified crowns shape (semi-spherical).

The goal of this research is to evaluate the fatigue resistance of five CAD/CAM ceramic restorative materials used for treating broken lower first molar under typical occlusal loads found in clinical applications, Y-TZP zirconia, lithium disilicate (LD), and lithium (di)-silicate/phosphate glassceramics. Using 3D FEA, the fatigue life of restorative materials is measured. The null hypothesis was that there would be no fatigue resistance difference in the materials (with distinct compositions, with distinct microstructure).

2. Materials And Methods

The fatigue behavior of five restorative materials; two yttria-stabilized tetragonal zirconium dioxide (3Y-TZP), (LAVA (LVs), EVEREST (KVs)); a lithium disilicate LD (IPS e.max CAD Ivoclar-Vivadent); two lithium (di)-silicate/phosphate glassceramics (Suprinity PC and Celtra Duo), are estimated. Table 1 describes the materials used, their manufacturers, and post-processes. Table 2 lists the mechanical properties of the restoration materials used. The materials selected in this analysis have been chosen to cover a wide variety of newly developed restorative materials currently available on the market.

Table 1
Description of materials used, their manufacturers, post-processes

Material	Commercial name (manufacturer	Processes	Ref
3Y-TZP sandblasted	LAVA (LVs) 3M Espe, Seefeld, D	Roughness (μm) = 0.26 Sample: Bars 40 mm × 3 mm × 5 mm, each bar was subjected to four firing cycles (930°C, 900°C, 890°C, 880°C)	[12]
3Y-TZP sandblasted	EVEREST ZS (KVs) KaVo Dental GmbH, Biberach, D	Roughness (μm) = 0.71 Sample: Bars 40 mm × 3 mm × 5 mm, each bar was subjected to four firing cycles (930°C, 900°C, 890°C, 880°C)	[12]
lithium disilicate	IPS e.max CAD Ivoclar-Vivadent	e.max CAD specimens underwent a crystallization firing for 8min at 840 ∘C (heating rate 55 ∘C/min) or 10min at 850 ∘C (heating rate 30 ∘C/min)	[10]
Pre-sintered Lithium Silicate/phosphate (LSP) glass-ceramic	Suprinity, VITA Zahnfabrik	e.max CAD specimens underwent a crystallization firing for 8min at 840 ∘C (heating rate 55 ∘C/min) or 10min at 850 ∘C (heating rate 30 ∘C/min)	[10]
Fully-sintered lithium silicate/Phosphate (LSP)glass-ceramic	Celtra Duo, Dentsply DeTrey	Data not available from the ref. [19]	[10]

Table 2
Material properties for the restored first molar model.

Material	Young's modulus (GPa)	Poisson ratio (*v*)	Yield strength (MPa)	Flexural strength (MPa)	Compressive strength (MPa)	Shear strength (MPa	ref
Indenter (mechanical properties similar to enamel)	84.1	0.33		11.5	384	60	[13]
3Y-TZP (LVs)	205.2	0.32		1282			[12]
3Y-TZP(KVs)	205.2	0.32		836			[12]
LD (IPS e.max CAD)	102.7	0.215		338.5			[10]
(LSP) Celtra Duo	107.9	0.222		488.2			[10]
(LSP) Suprinity	104.9	0.208		328.7			[10]
Dentin	18.6	0.31		105.5	267	12–138	[13]
Dual cure resin cement thickness 0.05–0.08 mm for full zirconia,	8	0.3				34.4	[13]
Die (grade 4 Gypsum)	14	0.35	29				[13]

A 3D model was obtained by a 3D scanner of the lower first molar crown and shown in Fig. 1. The model consists of a crown, layers of cement, and death (dentine). The sample Stereolithography (STL) files are imported into solid modeling software (SolidWorks 2018, DS Solidworks Corp, USA). The model is transferred into the FEA software (ANSYS, Inc., USA). A 6 mm hemispherical indenter is used and is made of material with enamel-like mechanical properties. A 50 µm thick layer of adhesive resin cement is molded.

The key steps to clinically predict the long-term survival of dental restoration are a) obtain fatigue data from laboratory experiments, b) evaluate the actual multi-state stresses under the oral load in the actual crown restoration, and c) use appropriate fatigue failure theories.

Two types of loads are studied, the first type: a compressive force acting in the tooth axial, the second type: axial load followed by a sliding motion. The model of the first molar under axial loading is shown in Fig. 1(right). The model is fixed on the lower surface. The life of two clinical years is believed to equate to one million cycles. The frictional interaction between occlusal surfaces and indenters is simulated. Furthermore, the crown is thought to be perfectly bonded with dentin.

Static test is conducted to simulated the occlusal load using a hemispherical indenter. Nine samples are manufactured. A 3D finite element model is constructed that simulates the real experimental setup. The sample preparation techniques can be summarized as follows; nine silicone impressions (3M ESPE, United States) were made in order to duplicate the prepared plastic tooth for the first mandibular molar (Nissin Dental Model, Japan), all impressions poured into type IV gypsum die (Dentona gypsum material, Germany). Each master dies derived from one of the nine recorded impressions was then scanned (Dentsply Sirona in EosXF, United States), and used to design zirconium full contoured crowns using CAD/CAM system using (Sirona CAD/CAM Mcx5milling machine Software inlab sw16.1). For zirconia, the corresponding occlusal crown thickness was 1,4 mm. 0.8 mm is the proximal wall thickness. A thickness of 50 μm of cement is used. The crown's STL file was produced and sent to the milling unit. Following the instructions of the manufacturer, all specimens were sintered in a sintering furnace after the milling process ended. Crowns is seated and cemented using dual-cure resin cement Panavia cement on the gypsum dies (Kuraray America Inc, USA). The indenter is located and balanced on the occlusal surface so that it has three points of contact with the crown. The crowns were then subjected to axial compressive load centered in the central fossa until fracture. A radius of 3.8 mm was selected for the spherical indenter. The load was applied at a cross-head speed of 0.5 mm/min on a computer-controlled electromechanical universal testing system (Model WDW-20).

3. Results

The flexural strength for the studied materials are in the following order: LAVA (1282 MPa > EVEREST (836 MPa) > IPS e.max CAD (488.6MPa) > Celtra Duo (338.5 MPa) > Suprinity PC (328.6 MPa). It was found that the fatigue limit ranges between 37% and 73% of the monotonic flexural strength for all the materials tested. The fracture loads measured in the static test range between 2350 and 2450 N. For the particular spherical indenter on three-cusp loading configuration, all the samples have fractured at the same location, which slightly off the symmetry fissure plane between cusps.

The stress distribution of two CAD/CAM materials under various axial load values is shown in Fig. 2. For LD crowns under an axial load of 100 N, the maximum principal stress is 55.28, while for LD crowns it reaches 245 MPa under an axial load of 600N. Under a load of 800 N, the maximum tensile stress for the Y-TZP LAVA crowns is 439.20 MPA, and 517.03 MPa under an axial load of 1000 N. Figure 3 shows the predicted lifetime for the crown tested in this study under two loading types; axial and axial load followed by a sliding motion. For all material studies under an axial load of 185 N, the FEA predicts that the fatigue life will be longer than 10 years. In addition, FEA results show that crowns made of LAVA and EVEREST zirconia can last longer than 10 years under an axial load of 1045 0N. Applying the second type of load, the lives of crowns decrease by 16% on average.

4. Discussion

The essential issue of this study was to determine whether fatigue behavior of dental materials depends on the composition, manufacturing process, surface roughness. The simulation result shows that fatigue resistance is different among the materials studied, thus the null hypothesis is rejected. The findings of the current study are in good agreement with previous studies that fatigue resistance of zirconia is much better than LD [14]. Cyclic loading decreases the strength of the restoration at a rate that depends on the microstructure, composition, and heat treatment processes. The strength of the zirconia material drops significantly at the very early-stages (less than a day), but almost remains flat afterward. The amount of strength degradation for Lava zirconia reaches up to 33% in the first day, while the strength of decreases by 17%. The fatigue limits are nearly 65% and 77% of monotonic flexural strength of Y-TZPs Lava and Everest, respectively. The reason behind the flatting of the S-N for the two Y-TZPs materials is the application of sandblasting. The strength of IPS e.max CAD drops 25% in the first day, and the strength degradation rate remains almost constant. The fatigue limit is around 45% of flexural strength. Similar behavior is observed for Suprinity PC and Celtra Duo, early stage strength reduction around 28%. The fatigue limits for Suprinity PC and Celtra Duo are 44% and 38% of the flexural strength respectively. For polycrystalline zirconia materials, softening does occur when subjected to fatigue loading, but the rate of reduction (slope) varies significantly depending on the heat treatments, post-processing, and the manufacturer. Sandblasting increases the initial strength, but most significantly, for long-term fatigue strength, the increase is greater. The fatigue behavior of Y-TZP ceramic materials was improved by sandblasting by at least 20%.

Regardless the differences in fatigue resistance among tested EVEREST, LAVA, and LD, the fracture load corresponding to five years of clinical life is better than those seen in the standard clinical setting (for males – 285 ± 149 N up to 462 ± 199 N and for females 254 ± 131 N up to 446 ± 175 N, irrespective of age) [15, 16]. The Suprinity PC and Celtra Duo might not be appropriate for those individual with high chewing load. The glass-ceramics crowns may be quite suitable for anterior region [2], when placed in the posterior region, they do not present survival percentage as high as zirconia crowns [17]. Therefore, the simulation results show that Y-TZP materials are suitable for clinical application regardless the gender and age.

The life of all-ceramic crown materials was predicted by FEA and found to conform to previous experimental and clinical observations. While this study effectively mimics the clinical situation to a large degree, in particular the orientation of forces involved in the oral masticatory system, it has suffered many limitations. The limitations of this analysis could be summarized as follows; deterioration of low temperatures, sensitivity to the presence of notches and irregularities, and the impact of variations in pH were not taken into account.

5. Conclusion

The results demonstrated that there is a significant difference between the fatigue resistance as a function of the material used in the monolithic restoration, rejecting the null hypothesis. The simulation results show that Y-TZPs materials have higher fatigue performance than LD and LDP. Experimental findings show that all the samples have fractured at the same spot, which is slightly deviated between cusps from the symmetry fissure axis. The fatigue life for the Y-TZP zirconia exceeded 10 years under the two types of loads studied (axial load of 1000 N and axial load 900 followed by sliding). The fatigue life of lithium disilicate is higher than the lithium (di)-silicate/phosphate glass-ceramics. Under cyclic loading, the strength of all the materials studied decreases with various reduction rates depending on composition, treatments and post-processing.

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Figures

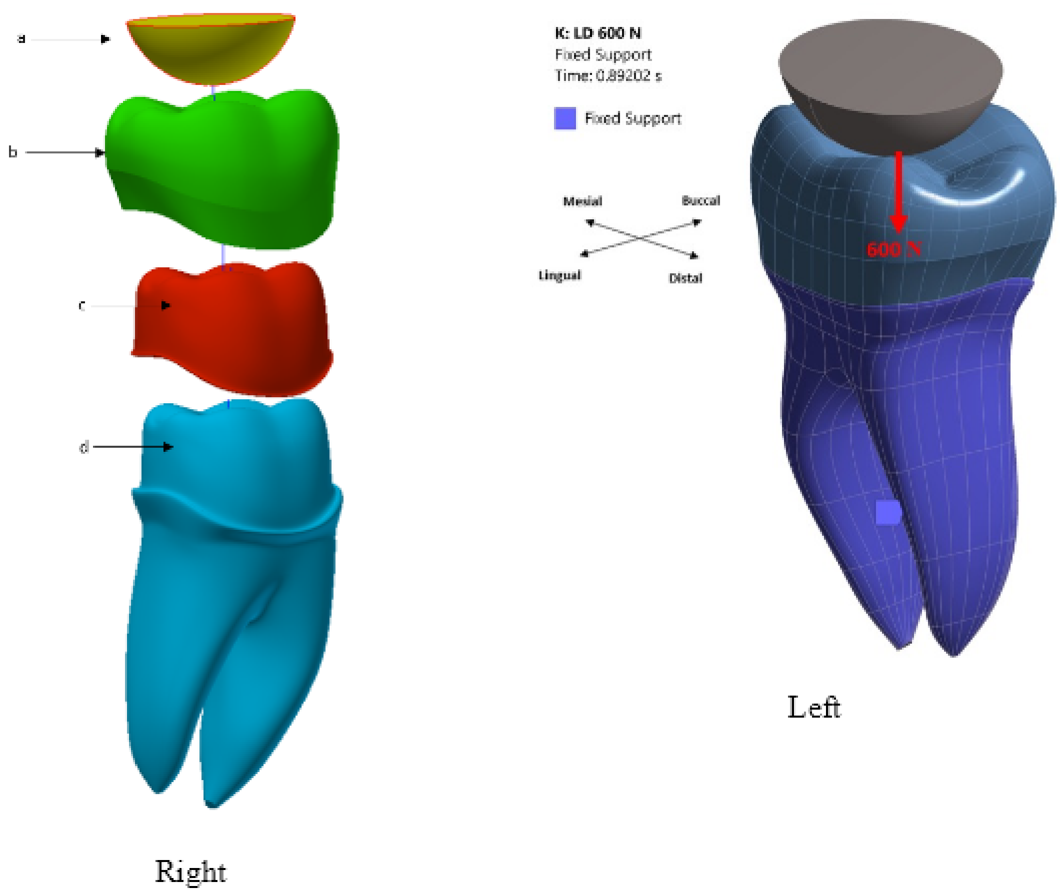


Figure 1

Left:3D model of the restored first molar, right: Boundary conditions and applied loading (arrow) for the used model from two different views: mesial/buccal (upper) and distal/lingual (bottom)

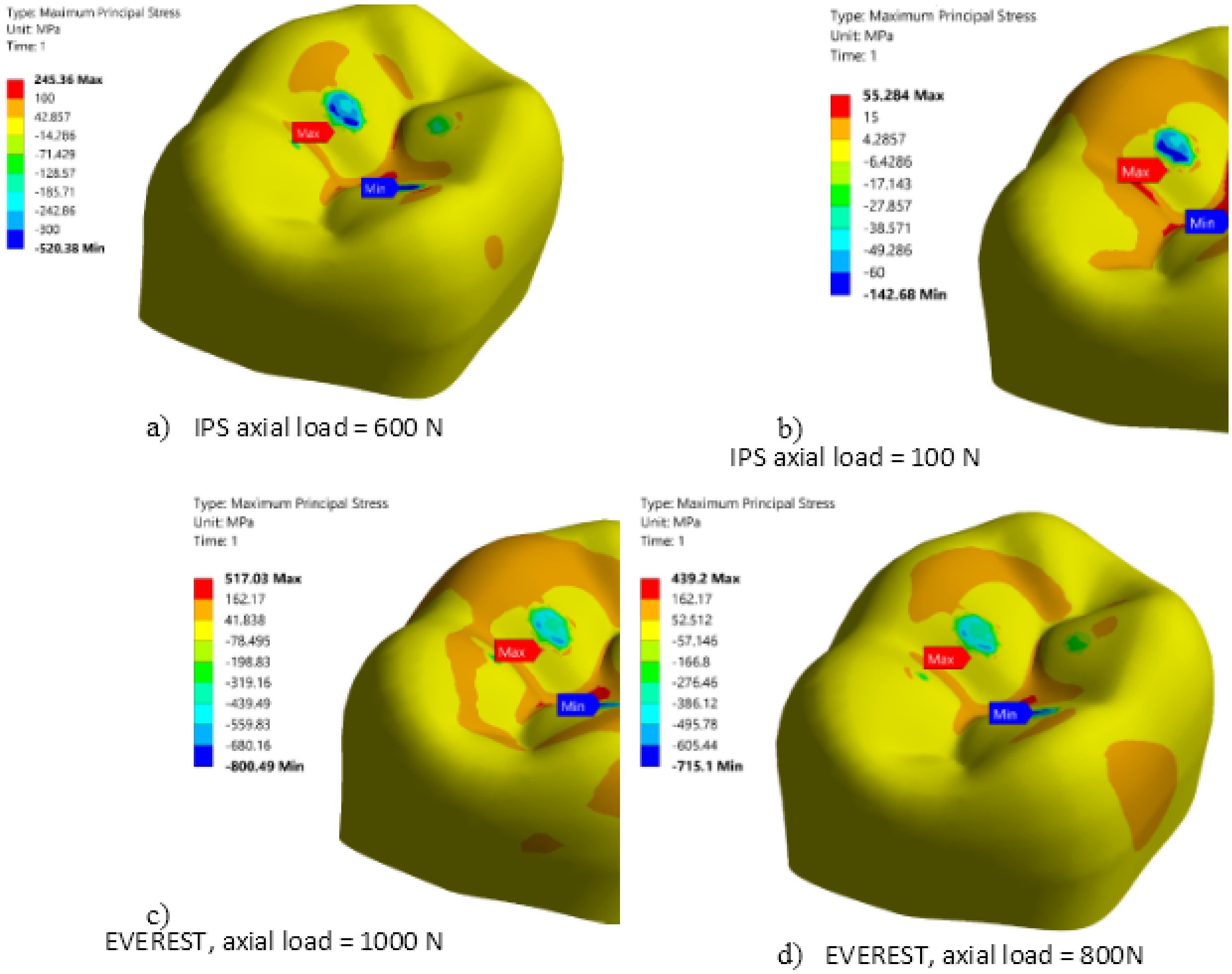
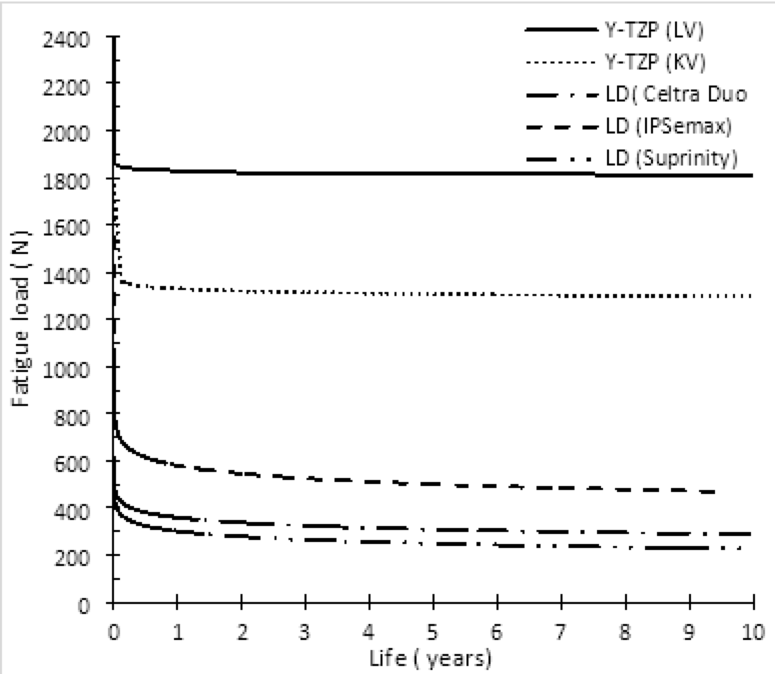
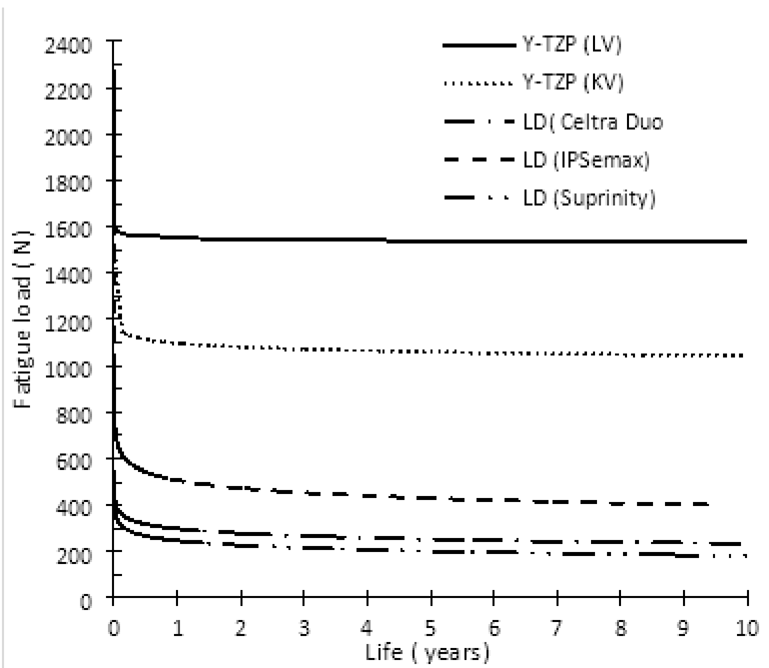


Figure 2

Max tensile stress distribution for the two EVEREST KV and IPS e.max CAD materials at different axial loads.



a)



b)

Figure 3

Fatigue life for the crowns tested under two loading conditions, a) axial loading, b) oblique loading.