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# Approximate relative fatigue life estimation methods for thin-walled monolithic ceramic crowns

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ABSTRACT

*Objectives.* The objective is to establish an approximate relative fatigue life estimation method under simulated mastication load for thin-walled monolithic restorations.

*Methods.* Experimentally measured fatigue parameters of fluormica, leucite, lithium disilicate and yttrium-stabilized zirconia in the existing literature were expressed in terms of the maximum cyclic stress and stress corresponding to initial crack size prior to N number of loading cycles to assess their differences. Assuming that failures mostly originate from high stress region, an approximate restoration life method was explored by ignoring the multi-axial nature of stress state. Experiments utilizing a simple trilayer restoration model with ceramic LD were performed to test the model validity.

*Results.* Ceramic fatigue was found to be similar for clinically relevant loading range and mastication frequency, resulting in the development of an approximate fatigue equation that is universally applicable to a wide range of dental ceramic materials. The equation was incorporated into the approximate restoration life estimation, leading to a simple expression in terms of fast fracture parameters, high stress area $\Delta A$, the high stress averaged over $\Delta A$ and N. The developed method was preliminarily verified by the experiments. The impact of fast fracture parameters on the restoration life was separated from other factors, and the importance of surface preparation was manifested in the simplified equation. Both the maximum stress and the area of high stress region were also shown to play critical roles.

*Significance.* While nothing can replace actual clinical studies, this method could provide a reasonable preliminary estimation of relative restoration life.

## 1. Introduction

Ceramic crowns are widely used due to their improved biocompatibility and esthetic appeal compared to the more traditional metal-based restorations. With the availability of high strength ceramic materials such as zirconia [1] and lithium disilicate [2], it has become possible for clinicians to make thin-walled monolithic crown similar to metal [3]. However, ceramics are brittle, and failure from fracture continues to be a major concern [4]. While it is understood that restoration geometry, loading conditions, surface preparation,

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environmental fatigue, and ceramic properties play a role in restoration survival, there is no clear understanding as to how each factor influences restoration lifetime. Currently, there is no easy way to estimate the relative fatigue survival rate of monolithic crowns.

A systematic review of all-ceramic crown survival suggest that many ceramic systems showed 5-year failure rates similar to metal ceramics [5]. Analysis of the complications indicated that porcelain chipping [6], especially with the high strength ceramics, was responsible for many of the reported failures and that substructure fractures were reported much less frequently. These clinical observations have moved the profession toward the use of monolithic ceramic crowns particularly for the restoration of posterior teeth.

The fractographic analyses of clinically failed crowns has improved our understanding of crown failure modes. Early all-ceramic monolithic materials such as fluromica (FM) showed that most of the failures occur due to fracture initiated from the intaglio surface [7]. For higher strength ceramic materials such as lithium disilicate (LD), yttrium-stabilized zirconia (YZ), and alumina, failure initiation from the wall-margin area has also been reported [8,9]. As the profession moves away from layered ceramic structures and toward the use of thinner-walled monolithic structures, it is anticipated that porcelain chipping will be less common failure mode and interface initiated fractures will be a more dominant fracture mode.

A number of 3D finite element (FE) models of complete restorations have been analyzed to identify high stress areas [10]. In addition, failure probability analysis software such as CARES [11] has been employed to predict fatigue life of dental restorations [12]. All these analyses were based on the maximum principal stress. More recently, focusing on realistic multi-axial stress state, Nasrin et al. [13] predicted fatigue life of actual restoration and verified the model against experimental data with a simple trilayer model restorations.

In this work, we propose a simplified approach to estimate fatigue life of thin-walled monolithic restoration. For this purpose, a wide range of representative dental ceramic materials, FM, LD, YZ and leucite reinforced glass-ceramic (LR), where material parameters were available in the existing literature, were chosen for analysis. A universal approximate fatigue equation applicable to all dental ceramic materials was developed and incorporated into crown life estimation. The fatigue survival rates of trilayer specimen with LD cemented to dentin/dentin substitute were experimentally determined and used to verify the proposed approximation method. The effect of LD thickness on stress distribution and corresponding approximate fatigue life estimation were also examined.

## 2. Material and method

### 2.1. Parameter conversion

#### 2.1.1. Fast fracture parameter conversion

To analyze the effect of multiaxial stress state on fracture initiation from surface flaws at the intaglio surface, statistical failure probability model by Batdorf and Cross [14] (Appendix A) was employed. Following the work of Chao and Shetty [15], surface flaws were characterized by the crack density function (the number of cracks with critical stress, $\sigma_{cr}$, per unit area), $N_{flaw}$, with parameters $m$ and $\bar{k}$ as follows,

$$N_{flaw} = \bar{k}\sigma_{cr}^{m}. \tag{1}$$

Weibull's scale and shape parameters, $\overline{\sigma_0}$ and $m$ (Appendix A), were determined by four point bending tests for LD [16] and FM [17] and by cantilever tests for YZ [18]. Considering the uniaxial stress case based on Batdorf's formulation [14,15] and comparing the resulting formulation with Weibull formulation, $\bar{k}$ in Batdorf's formulation was determined by

$$\frac{4m\bar{k}}{\pi} I_{A,uniaxial} A_{eff} = \left(\frac{1}{\overline{\sigma_0}}\right)^{m}, \tag{2}$$

where

$$I_{A,uniaxial} = \int_{0}^{\pi/2} \theta_{cr} \sin\theta_{cr} (\cos\theta_{cr})^{(2m-1)} d\theta_{cr}. \tag{3}$$

For each material, parameters $I_{A,uniaxial}$ and $A_{eff}$ (Eqs. (A3), (A4), (A6) in Appendix A) were evaluated based on experimentally measured values of $m$ and sample geometries.

Similarly, using Weibull parameters, $\overline{\sigma_0}$ and $m$ determined by Myers et al. [19] for LR based on biaxial tests, $\bar{k}$ in Batdorf's formulation was determined by

$$4\bar{k}mr_1^2 I_{A,biaxial} = \left(\frac{1}{\overline{\sigma_0}}\right)^{m}, \tag{4}$$

where

$$I_{A,biaxial} = \int_{0}^{1} \int_{0}^{\frac{\sigma_{cr}}{\sigma_{1,max}}} \theta_{cr} \left(\frac{r}{r_1}\right) \left(\frac{\sigma_{cr}}{\sigma_{1,max}}\right)^{(m-1)} d\left(\frac{\sigma_{cr}}{\sigma_{1,max}}\right) d\left(\frac{r}{r1}\right), \tag{5}$$

and

$$\theta_{cr} = \frac{1}{2}\cos^{-1}\left[\frac{2\sigma_{cr} - \sigma_{1,max} - \sigma_{2,max}}{\sigma_{1,max} - \sigma_{2,max}}\right]. \tag{6}$$

The radius of support circle in bi-axial tests was denoted by $r_1$, and the maximum tangential and radial normal stress at the bottom surface of the specimen at position $r$, were respectively represented by $\sigma_{1,max}$and $\sigma_{2,max}$. To evaluate $I_{A,biaxial}$, the stress distribution at the bottom surface of a disk sample was determined by axisymmetric finite element analysis (FEA) model (disk radius: 6 [mm]; thickness: 1 [mm]; radius of support ring: 4.74 [mm]; indenter radius: 0.3 [mm]) based on ABAQUS [20] following ASTM F394-78 standard employed by Myers et al. [19].

#### 2.1.2. Fatigue parameter conversion

To analyze fatigue crack growth (crack size $a$; time $t$), the power law with parameter $n$ and A was employed.

$$\frac{da}{dt} = AK^{n}, \tag{7.1}$$