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Fatigue of Zirconia and Dental Bridge Geometry: Design Implications

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Abstract

Zirconia is currently used as a framework material for posterior all-ceramic bridges. While the majority of research efforts have focused on the microstructure and corresponding mechanical properties of this material, clinical fractures appear to be largely associated with the appliance geometry.

Objective—The objective of this study was to estimate the maximum stress concentration posed by the connector geometry and to provide adjusted estimates of the minimum connector diameter that is required for achieving 20 years of function.

Methods—A simple quantitative description of the connector geometry in an all-ceramic 4-unit bridge design is used with published stress concentration factor charts to quantify the degree of stress concentration.

Results—The magnitude of stress concentration estimated for clinically relevant connector geometries ranges from 2 to 3. Using previously published recommendations for connector designs, adjusted estimates for the minimum connector diameter required to achieve 20 years of clinical function are presented.

Significance—To prevent clinical fractures the minimum connector diameter in multi-unit bridges designs must account for the loads incurred during function and the extent of stress concentration posed by the connector geometry.

Keywords

All-Ceramic Bridge; Fatigue; Stress Concentration; Zirconia

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Introduction

A recently article describes an investigation aimed at evaluating the fatigue behavior of an yttria-stabilized zirconia (3Y-TZP) and application of the results to develop guidelines for the design of dental bridges that achieve lifetimes exceeding 20 years of clinical function [1]. The authors present an interesting study of the crack propagation behavior of 3Y-TZP achieved under cyclic loading at stress levels that are approximately half those required to initiate fracture under monotonic loading. Experimental results are presented for the fatigue behavior in air and within aqueous conditions. Sub-critical crack growth parameters were determined from fitting power law models to results of the cyclic loading experiments. Then, a Wöhler diagram was constructed using the sub-critical crack growth parameters for the 3Y-TZP, along with results from a determination of the strength under quasi-static loading. The diagram provides a comprehensive description of the number of cycles to failure (i.e., the life) resulting from a particular maximum cyclic stress, and/or the critical cyclic stress for a desired life.

When reviewing the field of dental ceramics it becomes evident that the unique and desirable qualities of zirconia have been recognized for some time [2–4]. But one outstanding limitation to its widespread application in restorative dentistry is clinical longevity. Indeed, there is now greater emphasis on identifying and adopting clinically relevant in vitro test methods that provide more insight on the reliability of dental ceramics in vivo [5,6]. These comments are relevant to all dental ceramics. One of the many strengths of the presentation by Studart et al is an application of laboratory results quantifying the mechanical behavior of this ceramic to the clinical setting. First, the authors develop estimates for the maximum tensile stress in dental bridges of 3-, 4- and 5-unit configurations as a function of the connector diameter for a 250 N load on the pontics. The estimated stress distributions are then used with the mechanical properties determined from experiments to estimate the minimum connector diameter ($d_{\min}$) that reduces the probability of failure to less than 5% over 20 years of function. Of particular note, the estimated $d_{\min}$ accounts for fatigue induced by chewing and bulk fracture caused by severe clenching or grinding. According to a consideration of both modes of failure, the estimated $d_{\min}$ ranges from 2.7 mm < for the 3-unit bridge to 4.9 mm < for a 5-unit bridge. This approach has also been used in estimating the $d_{\min}$ for bridge designs constructed from a Al_2O_3 -ZrO₂ glass composite and a $\text{Li}_2\text{O}\cdot 2\text{SiO}_2$ glass ceramic [7].

Despite experimental results showing that 3Y-TZP is susceptible to water-assisted cyclic crack growth, the authors provide convincing evidence that it can be used successfully as a framework material for posterior all-ceramic bridges, provided that the connector is appropriately designed. Namely, the study highlights that it is essential to limit the magnitude of maximum stresses that develop under function by using a connector diameter greater than the estimated $d_{\min}$. But there is an important aspect of the multiple unit bridge geometry that was overlooked. Studart and coworkers simplified the calculation of stress by adopting a mechanics of materials approach where the bridge is modeled as a cylindrical beam simply supported between the two abutments. The stress induced by flexure is then estimated using beam theory according to the connector diameter. While this simplified calculation leads to higher stress levels than those estimated from finite element analyses available in the literature [1], this approach ignores the stress concentration posed by the non-uniform bridge geometry. To obtain truly conservative guidelines for the design of dental bridges, a thorough evaluation of the effect of bridge geometry on stress concentrations is required.

Theoretical Background

We illustrate the importance of bridge geometry and connector design taking a typical all-ceramic 4-unit bridge as an example (Fig. 1(a)). Features of geometry important to the stress concentration that develops with occlusal loading are indicated in Figure 1(b). Occlusal loading

of the bridge results in the development of a bending moment (M) acting over the length of the bridge. The simplification adopted by Studart et al [1] results in a linear stress distribution about the neutral axis, and a maximum tensile stress of σ_{nom} at the connector's surface (Fig. 1 (c)). However, the abrupt decrease in cross-section area at the connectors causes a stress concentration at the connector root and a maximum stress (σ_{max}) exceeding σ_{nom} . There is symmetry in the stress distribution about the neutral axis, but the region of criticality is in tension. By definition, the stress concentration (K_t) defines the ratio of maximum stress to either the nominal or net-section stress and $K_t \geq 1$. If the stress concentration posed by the connector geometry is small ($K_t \sim 1$), then the estimated maximum stress in the bridge is adequately described by the values presented by Studart et al., [1]. But if the K_t is appreciable, the maximum stress is substantially larger than σ_{nom} and the estimated d_{min} required to achieve 20 years of clinical function is insufficient. Of note, several 2D and 3D finite element studies have identified that "high" stress concentrations develop at the connector area [4,5,8–13]. Yet, no study has provided a quantitative description of the magnitude of K_t in terms of the bridge geometry. Thus, it is essential to look at the issue of stress concentrations in bridge designs a little further.

Stress concentrations that develop at the intersection of the pontics can be described according to some simple geometric features, including the connector diameter (d), the diameter at the pontics (D) and the radius of curvature at their intersection (ρ) as illustrated in Figure 1(b). Here, d and ρ are of primary interest. An examination of manufactured devices provides a representative range of these features and includes $3\text{mm} < d < 5\text{mm}$ and $0.2\text{mm} < \rho < 0.5\text{mm}$; this range is consistent with those used in earlier studies [e.g. 4,5,9,12]. Using common stress concentration factor charts [14] for beams subjected to bending, the influence of these geometric features on the K_t is shown in Figure 1(d); the K_t potentially ranges from approximately 2 to 3. Thus, using the formulation used by Studart and coworkers and accounting for the range in K_t estimated here, the maximum stress on the connector for a 4-unit bridge is determined and presented in Figure 2; the magnitude of maximum stress scales linearly with the K_t . Note that a maximum stress for $K_t = 1$ would be equivalent to that estimated in Figure 6 of the Studart paper. Also note that this same diagram could be prepared for the 3- and 5-unit configurations as well. Figure 2 emphasizes the importance of connector geometry on the magnitude of maximum stress. Indeed, fractographic evaluations of all-ceramic bridges have reported that failures typically originate from flaws within the connector region due to the stress concentration [5,15]. Results from *in vitro* experimental studies of all-ceramic bridges have supported these findings as well [16–18].

Application of the Theory: Estimating the Minimum Connector Diameter

In recognition of the importance of stress concentrations on bridge design and the maximum stress, it is necessary to estimate the adjustments required in the minimum connector diameter to achieve a desired life. Again, Studart et al [1] estimated the minimum connector diameters for 3-, 4- and 5-unit bridges for 20 years of function with a failure probability of 5%. For fatigue, these estimates were based on a maximum cyclic stress of 346 MPa, a value estimated directly from the Wöhler diagram and a mastication frequency of 1400 cycles/day. Using that quantity as a definition of the endurance strength, an estimate of the d_{min} required to prevent fatigue failure is shown in Figure 3. The necessary diameter to prevent fracture under a single cycle (i.e. clenching) is presented for comparison, but fatigue is clearly the critical concern. The required d_{min} for both modes of loading increases substantially with the K_t . Admittedly, there are two limitations to these estimates. The calculations assume that the strength distribution of the zirconia in the presence of the notch is equivalent to that exhibited by the flexure specimens tested by Studart et al [1]. Differences could exist due to the lower population of flaws in the vicinity of the stress concentration, and due to the difference in geometry between the connector and specimens, among others. These issues, particularly the fatigue

behavior of dental ceramics and the contributions of flaws, require further study. Nevertheless, the estimates for minimum connector diameter accounting for geometric features that are intrinsic to bridge design show that the estimates presented by Studart et al., [1,7] are very non-conservative. Instead, the minimum connector diameters shown in Figure 3 should be used as conservative guidelines in the development of 4-unit zirconia bridges for clinical applications.

Conclusion

In summary, 3Y-TZP may serve as an appropriate material for the fabrication of all-ceramic multiple unit posterior bridges, but it is critical that the bridge design accounts for the importance of geometric features on the maximum stress and the corresponding probability of failure.

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a)

b)

c)

d)

Figure 1.

All-ceramic bridge design and the importance of geometric features.

- a) a typical 4-unit bridge
- b) a schematic diagram of a 4-unit bridge and distinction of the important geometric features that define the stress concentration of interest. Note the highlighted radius of curvature (ρ) at the connector in the inset (*).
- c) a qualitative description of the stress field that develops due to the stress concentrator. M is the bending moment created by the transverse loads applied to the structure, akin to the moment that would develop in a bridge due to the occlusal loads.
- d) a quantitative description of the stress concentration factor in terms of the connector diameter and radius of curvature

Figure 2.

The maximum stress in the connector as a function of the connector diameter and the radius of curvature at the intersection of the pontics. Results are shown for a maximum diameter of $D=6$ mm. Note that the maximum stress for a stress concentration factor of 1 is equivalent to the estimates presented by Studart et al., [1].

Figure 3.

The minimum connector diameter for a 4-unit all-ceramic bridge constructed from 3Y-TZP that is necessary to achieve a life of 20 years with probability of failure of 5%. Note the estimated minimum diameter for a radius of curvature of infinity ($\rho \rightarrow \infty$) is equivalent to the geometry assumed by Studart et al., [7] (i.e. no stress concentration).