Prediction of the Biomechanical Behavior of All-Ceramic Dental Restorations after Cyclic Loading using FEA

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Abstract. The mechanical performance of dental ceramic materials is commonly approached experimental by measuring the fracture strength, which reflects its static behavior. In normal service dental restorations are loaded far below their critical load, either continuously or under repetitive conditions. Unlike static stress, which is analyzed with calculations for a single stress state, fatigue damage occurs when stress at a point changes over time. The objective of the present study is to compare alternative loading areas of molar zirconia crowns with different designs, veneered with various overpressing ceramics and to predict the biomechanical behavior of the prosthetic restored teeth after cyclic loading, using a FEA. The fatigue behavior of various all-ceramic restorations will be investigated using a wide range of load levels (400-3200 N) till 10⁸ cycles, during axial and para-axial loading. The Fatigue Safety Factor was calculated, and values less than one indicated failure before the design life is reached. The failure behavior was interpreted relative to the load levels, areas, and restoration designs. Axial loading led to fatigue failure at lower loads (500 N) compared to para-axial loading (2000 N). Related to the crown design, the failure behavior didn’t change significant.

1. Introduction
Understanding mechanical properties is the first step to estimate clinical performance of biomaterials. Moreover, the data are always required for finite element analysis (FEA) which has become exceptionally popular in modern biomaterials science research [1]. Fracture toughness (KIC) which is a prominent factor to fracture of brittle materials, reveals resistance of material against crack extension [2]. For all-ceramic restorations zirconia framework design and the veneering material may influence the biomechanical behavior of the restoration [3]. In current practice, the framework of all-ceramic bilayered crowns is obtained by milling an even thickness copies, rather than using a scientific-based design. The continuously developing possibilities of actual CAD softwares allow achieving digital improved designs of the frameworks, regarding the control of the veneer thickness in case of the cutback designs [4]. Among all mechanical parameters, the most crucial one for dental restorations is fatigue behavior as it is the major cause of failures [5,6]. The stress-life (Wöhler) curve is the oldest way to characterize the fatigue resistance against cyclic loading [7]. It shows the relationship between the stress...
amplitude (sa) and the number of cycles to failure (N) [8]. This method not only shows the fatigue limit, but also predicts the number of cycles in the given fatigue load.

In the past, it was thought that brittle materials like ceramics do not suffer fracture due to fatigue in ambient temperature. This belief came from the fact that plastic deformation causes fatigue and as the plastic deformation in brittle materials is not evident, they cannot undergo fatigue. Fatigue circumstances have now been found in ceramics, although the mechanism seems to be due to degradation of toughening rather than plastic deformation [9].

Different studies investigated the fatigue behavior and longevity of ceramic materials, but only for specific load levels and a limited total number of cycles of $10^4$ [10-13]. However, no research has been conducted on fatigue behavior of various CAD/CAM ceramics using a wide range of load levels. Therefore, with the rapid development of the CAD/CAM ceramics in dentistry, there is a need to understand, predict and compare the fatigue behavior of those ceramics [14].

2. Aim of the research

The objective of the fatigue investigations was to compare alternative loading areas of molar zirconia crowns veneered with various overpressing ceramics and to predict the biomechanical behavior of the prosthetic restored teeth based after cyclic loading.

3. Materials and methods

For the experimental analyses, a maxillary first molar was chosen. A nonparametric modeling software (Blender 2.57b) was used to obtain the 3D tooth shape. The collected data were used to construct three dimensional models using Rhinoceros (McNeel North America) NURBS (Nonuniform Rational B-Splines) modeling program. Beginning from the anatomic contour of the crown, the tooth prepared for all-ceramic bilayered crowns with a 1 mm chamfer margin. The occlusal surface was then reduced by 1.5–2 mm. The axial walls were prepared with 6° convergence.

Two geometric models with differential coping designs were developed, framework designs suggested by the soft of the CAD/CAM system Cercon Art 3.2 (Degudent, Hanau, Germany). First, a uniform thickness of 0.5 mm was chosen for the framework. Second, a cutback design was prepared as same as for metal-ceramic crowns in order to obtain uniform, adequate thickness and support for the veneering ceramics. It was assumed that prosthetic crowns were made of zirconia-based ceramic veneered with overpressing lithium disilicate reinforced ceramics. For all cases a digital model of the bilayer crown was designed to occupy the space between the original tooth form and the prepared tooth form.

The geometric models were imported in the finite element analysis software ANSYS and meshed. To perform calculations, each tooth model was divided into a structural solid elements joined in nodes. The nodes on the bottom surface of the abutment tooth were constrained in all directions. The crown materials were assigned using literature data. The interfaces between models where modelled automatically by ANSYS (the type was bonded, and the behaviour symmetric). In order to simulate the stress distribution, the Young’s module and Poisson’s ratios were introduced: Young’s modulus (GPa) 18 for dentin, 64 for glass ceramic, and 205 for zirconia and Poisson’s ratio 0.27 for dentin, 0.21 for glass ceramic, and 0.31 for zirconia.

Different loading values were assumed. A distributed load between 400 N and 3200 N was applied in the central fossa area of the crown models (axial) and on the cusp slope (para-axial), to the direction of insertion by a 3D finite element ball model (6 mm in diameter). Characterizing the capability of a material to survive the many cycles a component may experience during its lifetime is the aim of fatigue analysis.

The ANSYS Fatigue Module supports a wide variety of fatigue analysis. The comprehensive calculations and results enable engineers to evaluate their designs for avoiding failures under real world conditions. Stress Life is based on S-N curves (Stress – Cycle curves) and has traditionally dealt with relatively high numbers of cycles and therefore addresses High Cycle Fatigue (HCF), greater than $10^5$ cycles inclusive of infinite life.

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4. Results and discussions
Unlike static stress, which is analyzed with calculations for a single stress state, fatigue damage occurs when stress at a point changes over time. Constant amplitude, proportional loading was chosen. A total number of cycles between $10^6$ and $10^8$ was investigated.

Once the type of fatigue analysis and the loading type were chosen, the next decision is whether to apply a mean stress correction.

For Stress Life mean stress can be accounted for directly through interpolation between material curves. Fatigue Life can be determined over the whole model. The contour plot shows the available life for the given fatigue analysis. If loading is of constant amplitude, this represents the number of cycles until the part will fail due to fatigue.

Fatigue Safety Factor is a contour plot of the factor of safety with respect to a fatigue failure at a given design life. The maximum Factor of Safety displayed is 15. For Fatigue Safety Factor, values less than one indicate failure before the design life is reached [15].

For 400 N cyclic loading the safety factor was over 1 in all cases, regardless of design and loading area (Figures 1, 2).

For 500 N cyclic loading the safety factor was under 1 in cases of para-axial loading, leading to failure at $7.5 \times 10^5$ cycles (for an uniform thickness of the veneer) and $3.44 \times 10^5$ cycles (for an uniform thickness of the framework). For axial loading the safety factor becomes smaller than 1 for cyclic loading with 3200 N, at $5.52 \times 10^4$ cycles (for an uniform thickness of the veneer) and $5.63 \times 10^4$ cycles (for an uniform thickness of the framework) (Figure 3).

Figure 1. Fatigue Life and Fatigue Safety Factor in the bilayer ceramic molar crown with an uniform thickness of the veneer for a 400 N axial cyclic loading.

Figure 2. Fatigue Life and Fatigue Safety Factor in the bilayer ceramic molar crown with an uniform thickness of the veneer for a 500 N axial cyclic loading.

Figure 3. Fatigue Life and Fatigue Safety Factor in the bilayer ceramic molar crown with an uniform thickness of the framework for a 3200 N para-axial cyclic loading.
Registered Fatigue Safety Factor values for samples with different designs (uniform thickness of the veneer and uniform thickness of the framework) and loading areas (for axial and para-axial loading) are presented in Table 1.

Table 1. Fatigue Safety Factor values for all loaded samples.

| Force N | Axial loading | Para-axial loading |
|---------|---------------|--------------------|
|         | uniform thickness of the veneer | uniform thickness of the framework | uniform thickness of the veneer | uniform thickness of the framework |
| 400     | 7.9978        | 8.0029             | 1.0326            | 1.0265            |
| 500     | 6.3983        | 6.4023             | 0.74442           | 0.7984            |
| 1000    | 3.1991        | 3.2012             | 0.37221           | 0.36492           |
| 1500    | 2.1328        | 2.1341             | 0.24814           | 0.24328           |
| 2000    | 1.5996        | 1.6006             | 0.1861            | 0.18246           |
| 2500    | 1.2797        | 1.2805             | 0.14888           | 0.14597           |
| 3000    | 1.0664        | 1.0671             | 0.12407           | 0.12164           |
| 3200    | 0.99973       | 1.0004             | 0.11632           | 0.11404           |

There are no differences between the two types of crown designs in the axial load in terms of Fatigue Safety Factor. In case of para-axial loads, the lifetime of the restorations is extremely short. For this reason an occlusal balancing is needed as close as possible to ideal - which leads to a longer life of restorations.

5. Conclusions
Within the limitations of the studies, the following conclusions can be drawn:

- The fatigue behavior of various all-ceramic restorations was investigated using a wide range of load levels (400-3200 N) till 10⁸ cycles.
- Axial loading leads to fatigue failure at higher loads (3200 N) compared to the para-axial (500 N).
- Related to the crown design, the failure behavior didn’t change significant.
- The occlusal balancing is the most important factor for the lifetime of the restorations.

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