Failure analysis of various monolithic posterior aesthetic dental crowns using finite element method

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Abstract. The aim of the study was to assess the effect of material stiffness and load on the biomechanical performance of the monolithic full-coverage posterior aesthetic dental crowns using finite element analysis. Three restorative materials for monolithic dental crowns were selected for the study: zirconia; lithium disilicate glass-ceramic, and resin-based composite. Stresses were calculated in the crowns for all materials and in the teeth structures, under different load values. The experiments show that dental crowns made from all this new aesthetic materials processed by CAD/CAM technologies would be indicated as monolithic dental crowns for posterior areas.

1. Introduction

Due to the increased demand for restorations that look like natural teeth, monolithic ceramic and composite crowns are increasingly used. CAD/CAM technologies have become more widespread to process dental materials in recent years, because of the fact that classical technologies usually require a very long processing time in a well-controlled environment. Ceramic crowns, like zirconia and glass-ceramic, are biocompatible and aesthetic but they are brittle, and failure from fracture continues to be a major concern particularly on posterior teeth which are subjected to greater masticatory loads and more continuous function. Several high strength ceramic materials have become available and are being used in dental practices [2-4].

In addition to the ceramic blocks, which are more frequently used for CAD/CAM applications, composite resin-based blocks have been developed, with better mechanical properties [5]. There are also some advantages of resin composite blocks over conventional ceramic blocks. They are more easily adjusted, milled and repaired. Micro-tensile bond strength testing showed that resin composite has higher bond strength to resin-based adhesive materials than to glass–ceramics [6]. It was also been found that resin composite caused a significantly lower volume loss on antagonist enamel than ceramics did in two-body wear testing, which may help to preserve the functional balance of dentition [7]. These materials are often introduced into the market without a basic understanding of their clinical performance because long term controlled clinical trials are not required and are both time-consuming...
and expensive. The development of experimental methods could be useful to help predict clinical behaviour of these new restorative materials.1

Finite element analysis (FEA) is a powerful and flexible computational tool to model dental structures and devices, simulate the occlusal loading conditions and predict the stress and strain distribution. It has been widely used in the dental and medical fields since the 1970s and has been proven to be accurate and efficient for finding solutions for complex geometry problems [8,9].

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2. Purpose

The aim of the study was to construct finite element (FE) models for monolithic full-coverage dental crowns for molars and premolars, comparing the stress distribution between zirconia, glass ceramic and composite materials, and revealing the effect of material stiffness and load on the biomechanical performance of the dental crowns.

3. Experimental part

For the experimental analyses a maxillary right first premolar and a maxillary right first molar were chosen. They were designed with a preparation for full-coverage crowns according to the guidelines of the prosthetic material manufacturers. The preparation included a 1.5-mm occlusal reduction, a 1.0 mm axial reduction, a 6-degree angle of taper, a 1-mm circular chamfer shoulder. Three restorative materials for monolithic dental crowns were selected for the study, each in the form of commercially available CAD/CAM blocks: zirconia; lithium disilicate glass-ceramic; and resin-based composite with ceramic filler.

Geometric models of the monolithic crowns were designed to occupy the space between the original tooth form and the prepared tooth form. At first nonparametric modeling software (Blender 2.57b) was used to obtain the 3D tooth shapes. The collected data were used to construct three dimensional models using Rhinoceros (McNeel North America) NURBS (Nonuniform Rational B-Splines) modeling program. The geometric models were imported in the finite element analysis software ANSYS, meshed and finite element calculations were carried out. The finite element model was solved under a variety of load case-material property combinations (Figure 1).

The nodes on the bottom surface of the abutment tooth were constrained in all directions. The crown materials were assigned using literature data. In order to simulate the stress distribution, the Young’s modulus and Poisson’s ratios were introduced: Young’s modulus (GPa) 18 for dentin, 16 for composite, 64 for glass ceramic, and 205 for zirconia and Poisson’s ratio 0.27 for dentin, 0.24 for composite, 0.21 for glass ceramic, and 0.31 for zirconia. The following loading situations were examined respectively: load applied at an average human bite force of 200 N and a maximum bite force (600 N for premolars and 800 N for molars). The simulated bite force was distributed across contact areas with antagonists.
The distribution of the principal stress and the equivalent stress, and also the maximal values were determined.

4. Results and discussions

Stresses were calculated in the crowns for all materials and in the teeth structures, under different load values (Table 1-4, Figures 2,3).

**Table 1.** Maximal principal stresses in the molar crowns and dentin for a 200 N loading

| Maximal principal stress values [Pa] | Crown      | Dentin     |
|-------------------------------------|------------|------------|
| Zirconia                           | 3.23x10^7  | 2.02x10^6  |
| Glass ceramic                       | 4.07x10^7  | 1.69x10^6  |
| Composite                           | 4.16x10^7  | 2.72x10^6  |

**Table 2.** Maximal principal stresses in the premolar crowns and dentin for a 200 N loading

| Maximal principal stress values [Pa] | Crown      | Dentin     |
|-------------------------------------|------------|------------|
| Zirconia                           | 2.53x10^7  | 13.4x10^6  |
| Glass ceramic                       | 2.81x10^7  | 13x10^6    |
| Composite                           | 2.76x10^7  | 12x10^6    |

**Figure 2.** Principal stress distribution in the glass-ceramic molar crown and underlying dentin.

**Figure 3.** Principal stress distribution in the glass-ceramic premolar crown and underlying dentin.
Table 3. Maximal principal stresses in the molar crowns and dentin for a 800 N loading.

| Maximal principal stress values [Pa] | Crown     | Dentin    |
|-------------------------------------|-----------|-----------|
| Zirconia                           | 12.9x10^7 | 8.07x10^6 |
| Glass ceramic                       | 16.3x10^7 | 6.74x10^6 |
| Composite                           | 16.6 x10^7| 10.9x10^6 |

Table 4. Maximal principal stresses in the premolar crowns and dentin for a 600 N loading.

| Maximal principal stress values [Pa] | Crown     | Dentin    |
|-------------------------------------|-----------|-----------|
| Zirconia                           | 7.58x10^7 | 40.1x10^6 |
| Glass ceramic                       | 8.42x10^7 | 39x10^6   |
| Composite                           | 8.28x10^7 | 35.9x10^6 |

Compared to the tensile strength of the new aesthetic materials, 745 MPa for zirconia, and 360 MPa for glass ceramic, and 200 MPa for composite, the maximal principal stresses in the crowns don’t exceed them for 600 N in the premolar area and 800 N load in the molar area, for all type of materials. According to the literature data [10], that the tensile strengths of dentin ranged from 44.4 MPa to 97.8 MPa, no harmful effects occur in hard teeth structures, because in all cases first principal stresses in dentin are lower. The values approach the lower limit in case of premolar crowns and result in increased stress levels, eventually leading to a compromised long-term clinical performance.

The material is important to withstand increased loads which occur during functions. Reported loads during normal function vary considerably; there is no accepted consensus on either loads present in vivo or how they should be replicated in vitro. Some authors use lower loads, 100-200 N, others use loads in the range of 500-800 N [11].

It is not surprising that attempts would be made to substitute highly filled composite CAD/CAM blocks for ceramic blocks in fabricating full-coverage crowns [5]. In vitro testing studies compared CAD/CAM composite to ceramics favorably in terms of monotonic failure load and showed performance similar to veneering ceramics in fatigue loading [12-15]. However, dental composites have a discontinuous ceramic phase, and so are limited to much lower elastic modulus values than glass–ceramic materials. It has been found that thin-walled crowns made of low elastic modulus material (composite resin) are more prone to debonding than those made of stiffer materials such as ceramics. While thin-walled crowns of stiffer materials can protect tooth structures from damage better than composite resin ones. This lack of stiffness may result in increased stress levels under the same bite force compared to glass–ceramic restorations, eventually leading to a compromised long-term clinical performance.

Further investigations are still needed to analyze and evaluate the biomechanical behavior of this new type of aesthetic materials designed for dental crowns, relative to the material properties, processing technology and of course to the restoration design.

5. Conclusions

Within the limitations of the present study, the following conclusions can be drawn:

1. The distribution of principal stresses was not dependent on the bite force.
2. Maximal values of the principal stresses didn’t exceed the tensile strength values of the new aesthetic materials with improved mechanical properties.
3. Principal stresses were located at the contact areas with the antagonists and these areas can be starting points for the failure of aesthetic crowns in the posterior area.
4. Dental crowns made from all this new aesthetic materials processed by CAD/CAM technologies would be indicated as monolithic dental crowns for the posterior areas.
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