Stress analyses applications on all-ceramic crowns with different designs

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Abstract: Different studies available in literature regarding the analysis of all-ceramic restorations failures, investigated several parameters involved on the tooth structure - restoration complex, in order to improve clinical performances. Some of the parameters, like the framework design, are technique-sensitive during the manufacturing of the restorations and can easily influence the failure rates and fracture modes of final restorations. The goal of this study was to investigate the stress distributions of zirconia - all ceramic crowns with different designs, using varied stress distribution analyses. A static structural analysis was performed. Equivalent stresses were recorded in the tooth structures and in the restoration for all designs. Since ceramic materials exhibit brittle behavior, the first principal stress criterion was adopted to compare the stress values and distribution with those obtained for the first simulations. Under the same loading conditions, the stress distribution patterns for the zirconia all-ceramic crown using differential stress analyses exhibited similarities. The stress values are lower for the maximal principal stresses in all cases. The present study suggests that varied simulation methods are promising to assess the biomechanical behaviour of all-ceramic systems and first principal stress criterion is an alternative for ceramic materials investigations.

Key-Words: zirconia framework, ceramic veneer, crown, molar, simulation methods, finite element analysis, stresses.

1 Introduction

The performance of the all-ceramic crown was determined by many parameters. These included the fabrication methods, material selection for both the veneer and framework layers, tooth supporting structure preparation, magnitude and direction of occlusal loads, crown thickness and framework design [1-5]. Most studies have confirmed that the stresses increase with increasing loading magnitudes and the orientation of the load application substantially altered stress levels within the crown [5]. In general, crown strength improves with increasingly strong materials and increasing thickness [5]. After the shape of the preparation and materials of the crown had been determined, the only parameter that was manipulated by the operator was the coping design [6].

The trend for development of high-strength ceramics and its use in posterior areas has been a field of constant investigation [7,8]. Yttria-Stabilized Tetragonal Zirconia Polycrystals (Y-TZP) were introduced as framework material in attempt to reduce restoration bulk fracture. Its high mechanical properties have resulted in successful use of Y-TZP as a core ceramic in short- and medium-term clinical studies, where framework fractures were seldom reported [9,10]. While Y-TZP provides strength, the clinical success of these restorations has been hampered by fractures within the veneering porcelain. With regard to chipping and/or delaminating of the veneer, the performance of all-ceramic molar crowns fabricated with new CAD/CAM techniques is a subject of interest [11]. This material is indicated for posterior crowns but due to its high opacity requires veneering with glass ceramics. High strength zirconia core can be manufactured through CAD/CAM technology and subsequently veneered conventionally. According to in vivo observation, the clinical survival of zirconia-based restorations are comparable to metal–ceramic restorations [12]. In recent years it has become obvious that cohesive and adhesive failures of zirconia-ceramics veneered restorations often occur [13,14]. The studies available in literature focused on the analysis of all-ceramic restorations failures, investigating several parameters involved on the tooth structure - restoration complex, in order to improve clinical performances. Some of the parameters, like framework design, are technique-sensitive and during the manufacturing of the restorations can easily influence the failure rates and fracture modes of final restorations. In order to predict the clinical behavior of porcelain layered zirconia crowns, some studies evaluating fracture resistance have been performed [15,16]. The focus was on framework design and how different designs may influence possible. They show that the coping design affected the fracture load and the mode of fracture of zirconia all-ceramic crown [17].

Simulation-based medicine and the development of complex computer models of biological structures is becoming ubiquitous for advancing biomedical engineering and clinical research. Finite element analysis (FEA) has been widely used in the last few decades to understand and predict biomechanical phenomena. Modeling and simulation approaches in biomechanics are highly interdisciplinary, involving novice and skilled developers in all areas of biomedical engineering and biology. While recent advances in model development and simulation platforms offer a wide range of tools to investigators, the decision making process during modeling and simulation has become more opaque [18]. Establishing guidelines for model development and simulation, particularly for complex structures and different materials poses a challenge in the field of dental technology.

2 Purpose

The goal of this study was to investigate the stress distributions of zirconia - all ceramic crowns with different framework designs, using varied stress distribution analyses.

3 Materials and Method

For the experimental analyses a maxillary right first molar was chosen in order to simulate the biomechanical behaviour of the teeth restored with different zirconia - all ceramic crowns. The focus of the evaluations was on the framework design and how different coping designs may influence possible stress distributions. The die was designed with a chamfer finishing line and an 6° occlusal convergence angle of the axial walls was chosen for the preparation.

Two geometrical models of a bilayer crown were chosen for the investigations: first a uniform thickness of 0.5 mm for the framework and ceramic veneer designed to occupy the space between the original tooth form and the prepared tooth form, and second a cutback design in order to obtain uniform, adequate thickness and support for the veneering ceramics was developed.

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. In order to obtain a 3D solid model of the tooth, a surface following the cervical line was achieved, to close the surfaces.

The geometric models were imported in the finite element analysis software ANSYS, meshed and finite element calculations were carried out.

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 veneering ceramics, and 205 for zirconia and Poisson’s ratio 0.27 for dentin, 0.21 for veneering ceramics, and 0.31 for zirconia. To simulate physiological mastication behavior five loading areas were defined on the occlusal surface. Each defined loading area had a diameter of 0.5 mm. A total force of 250 N was allocated to these areas normal to the surfaces in each point. The bottom of the abutment teeth model was fully constrained for all simulations. A static structural analysis was performed to calculate stress distribution using a computer-aided software. Equivalent stresses were recorded in the tooth structures and in the restoration for all these designs. Since ceramic materials exhibit brittle behavior, the first principal stress criterion was adopted to compare the stress values and distribution with those obtained for the first simulations.

4 Results and Discussions

Stresses were calculated for all compunds of zirconia all-ceramic crown and teeth structures, for both designs and the distribution was plotted graphically (Table 1, 2, Fig. 1-6).

Table 1. Maximal equivalent stress and principal stress in crown compounds and dentin for the design with an uniform thickness of the framework.

Stress values in the structures	Maximal equivalent stress [MPa]	Maximal principal stress [MPa]
Ceramic veneer	206.74	45.89
Zirconia framework	47.79	31.59
Dentin	16.96	2.70

Table 2. Maximal equivalent stress and principal stress in crown compounds and dentin for the cut-back design.

Stress values in the structures	Maximal equivalent stress [MPa]	Maximal principal stress [MPa]
Ceramic veneer	203.57	54.87
Zirconia framework	110.14	18.64
Dentin	18.58	3.86

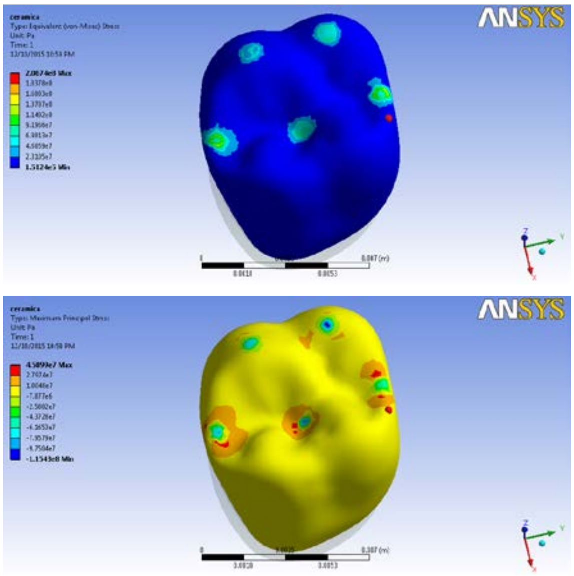

Fig. 1. Equivalent stress and principal stress distribution in the ceramic veneer for the design with an uniform thickness of the framework.

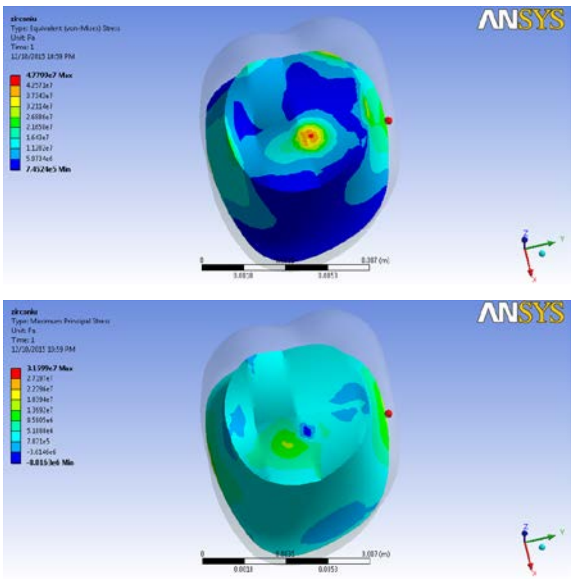

Fig. 2. Equivalent stress and principal stress distribution in the zirconia framework for the design with an uniform thickness of the framework.

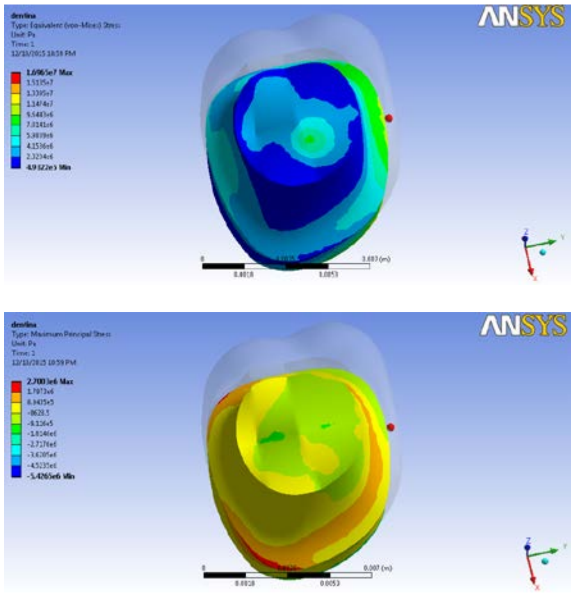

Fig. 3. Equivalent stress and principal stress distribution in the dentin for the design with an uniform thickness of the framework.

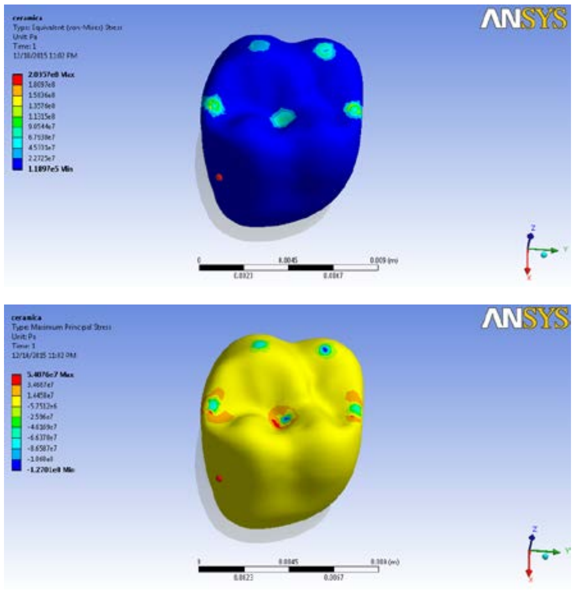

Fig. 4. Equivalent stress and principal stress distribution in the ceramic veneer for the cut-back design.

In all cases the values were higher in the veneers, equivalent stresses about four times greater than maximal principal stresses. Regarding the values in the frameworks, the equivalent stresses were higher when the framework was thicker, and the principal stresses vice versa. This is also valid for veneer. In the dentin stresses are insignificant higher for the cutback design.

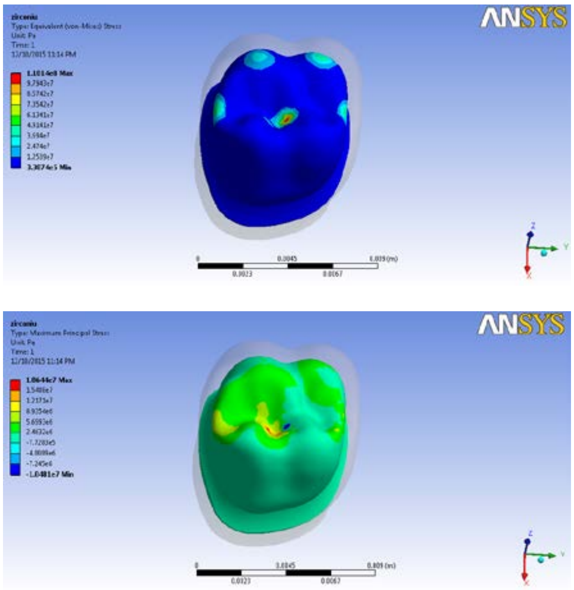

Fig. 5. Equivalent stress and principal stress distribution in the zirconia framework for the cut-back design.

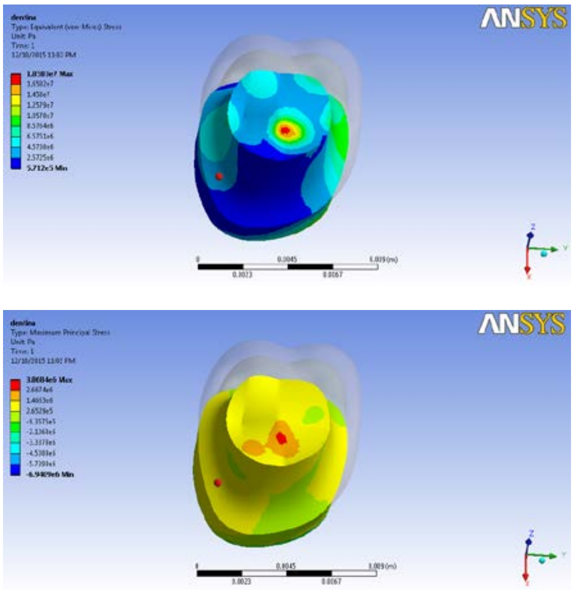

Fig. 6. Equivalent stress and principal stress distribution in the dentin for the cut-back design.

In the veneers stresses were distributed around the contact areas with the antagonists. The values of the maximal stresses in the frameworks are low and distributed occlusal and in the cervical areas buccal and oral. In dentin stresses are concentrated around the marginal preparation line, esecially for the design with an uniform thickness of the framework. Under the same loading conditions, the stress distribution patterns for the zirconia all-ceramic crown using differential stress analyses exhibited similarities. Only the values are lower for the maximal principal stresses.

According to different authors, the material will fail when the values of the equivalent stresses exceed the tensile strength of the material [19].

Factorial analysis performed studies showed that material and thickness of prosthetic crowns are of primary importance in stress magnitude. The higher the tensile strength of crown material, the thinner can be the crown's walls [5].

With the increasing number of FEA studies, FEA practice in biomechanics continues to pose a challenge for model development, sharing and reporting. In FEA, model definitions and development procedures are tightly coupled to the simulation method and the solver capabilities. FEA software commonly relies on embedded mathematical models of physical phenomena, e.g., solid mechanics. In many cases, decisions made during model development depend on the specific solver capabilities [18].

Because most FEA share common features during model development and simulation process, it is possible to compile parameters for reporting items that may be important for model reproducibility and may help the scientific community to assess the overall quality, scientific rigor, and utility of the model [18].

5 Conclusion

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

1. Varied simulation methods are promising to assess the biomechanical behaviour of all-ceramic systems and first principal stress criterion is an alternative for ceramic materials investigations.
2. FEA results can be used in rebuilding the design guidelines in CAD/CAM systems for zirconia all-ceramic restorations.
3. For the studied cases maximal equivalent stresses are directly proportional with the framework thickness, and maximal principal stresses indirectly.

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