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# Assessment of All-Ceramic Dental Restorations Behavior by Development of Simulation-Based Experimental Methods

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## Abstract

New dental materials are often introduced into the market and especially in the current practice, without a basic understanding of their clinical performance because long-term controlled clinical trials are required, which are both time consuming and expensive. Ceramic materials are known for their relatively high fracture resistance and improved aesthetics, but brittleness remains a concern. The stressed areas of the materials are key factors for the failure analysis, and numerical simulations may play an important role in the understanding of the behavior of all-ceramic restorations. Simulation-based medicine and the development of complex computer models of biological structures are becoming ubiquitous for advancing biomedical engineering and clinical research. The studies have to be focused on the analysis of all-ceramic restorations failures, investigating several parameters involved in the tooth structure–restoration complex, in order to improve clinical performances. The experiments have to be conducted and interpreted reported to the brittle behavior of ceramic systems. Varied simulation methods are promising to assess the biomechanical behavior of all-ceramic systems, and first principal stress criterion is an alternative for ceramic materials investigations. The development of well-designed experiments could be useful to help to predict the clinical behavior of these new all-ceramic restorative techniques and materials.

**Keywords:** all-ceramic restorations, design parameters, simulation methods, stress, biomechanical behavior

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## 1. Introduction

Ceramic materials and their technologies applied in dental field are in continuous development, but the clinical performance of all-ceramic restorations has to be improved due to the brittle nature of these materials.

As a consequence of brittle behavior, crack initiations and propagations in the materials can result in compromise of the restorations during functions and will be reflected in a poor clinical performance. In order to minimize clinical failures, restorations should be fabricated with consideration of their constituent material properties. Ceramic materials are known for their relatively high fracture resistance and improved aesthetics, but brittleness remains a concern [1]. The stressed areas of the materials are key factors for the failure analysis, and numerical simulations may play an important role in the understanding of the behavior of all-ceramic restorations.

New materials are often introduced into the market and especially in the current practice, without a basic understanding of their clinical performance because long-term controlled clinical trials are required, which are both time consuming and expensive. Simulation-based medicine and the development of complex computer models of biological structures are becoming ubiquitous for advancing biomedical engineering and clinical research [2–4].

In order to improve clinical performances of new all-ceramic restorations, studies have to be focused on the analysis of their failures, investigating different parameters involved in the tooth-restoration complex. Some of these parameters, like framework design, depend on the manufacturing technique and can be easily modified, influencing the failure rates and fracture modes of the restorations. How different designs may influence the fracture load and the mode of fracture of all-ceramic restorations is a topic of interest.

Finite element analysis (FEA) is a simulation method, widely used to understand and predict biomechanical phenomena in different areas of interest. Because modeling and simulation in dental field are complex, they involve skilled developers. With the advances in modeling and simulation, the clinical simulation becomes more real. 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. Establishing guidelines for model development and simulation, particularly for complex structures and different materials, pose a challenge in the field of dental technology.

Further studies are required to assess the durability of such restorations by different experimental methods before clinical use [5–7].

## 2. Digital design for all-ceramic crowns

The use of computer-aided design/computer-aided manufacturing (CAD/CAM) technology has grown in the last 30 years with the development of data acquisition technologies and computing technology. This led to improved quality restorations in terms of both resistance and adaptation to preparation and accuracy of occlusal morphology.

The evolution of these technologies has led to the widespread use of materials with superior mechanical and esthetic properties, like zirconia ceramics, which has the advantage that it can be used for almost any type of fixed prosthetic restoration.

It has been shown that resistance to fracture of ceramic restorations is not influenced only by the mechanical properties of the used material but also by the design of the preparations and the proper thickness of the restoration [8].

Traditionally, zirconia frameworks were fabricated at 0.5 mm thickness. Introduction of new types of zirconia served to reduce their thickness to 0.3 mm, allowing more conservative preparations [9]. Recommended finishing lines for these restorations are shoulder with rounded internal angles and slight chamfer, as a minimally invasive preparation designs, acceptable from both mechanical and periodontal reasons [8]. A point of interest is the effect of zirconia copings design on the resistance to load in posterior area, in order to prevent “chipping.” In current practice, the framework is obtained by milling even thickness copies, rather than using a scientific-based design [2]. The main reason for zirconia restoration failures is veneering ceramic fracture and chipping. These are caused by an inappropriate framework design, which cannot provide a proper support and thickness for porcelain veneer layer [10–12].

The following example suggests various designs for the framework of zirconia-ceramic molar crowns [13]. For the experiments, a maxillary right first molar prepared for all-ceramic crown was used. The tooth was prepared leaving a chamfer finishing line; with anatomical occlusal reduction, a 6° occlusal convergence angle and the palatal surface of the functional cusp were reduced in two planes.

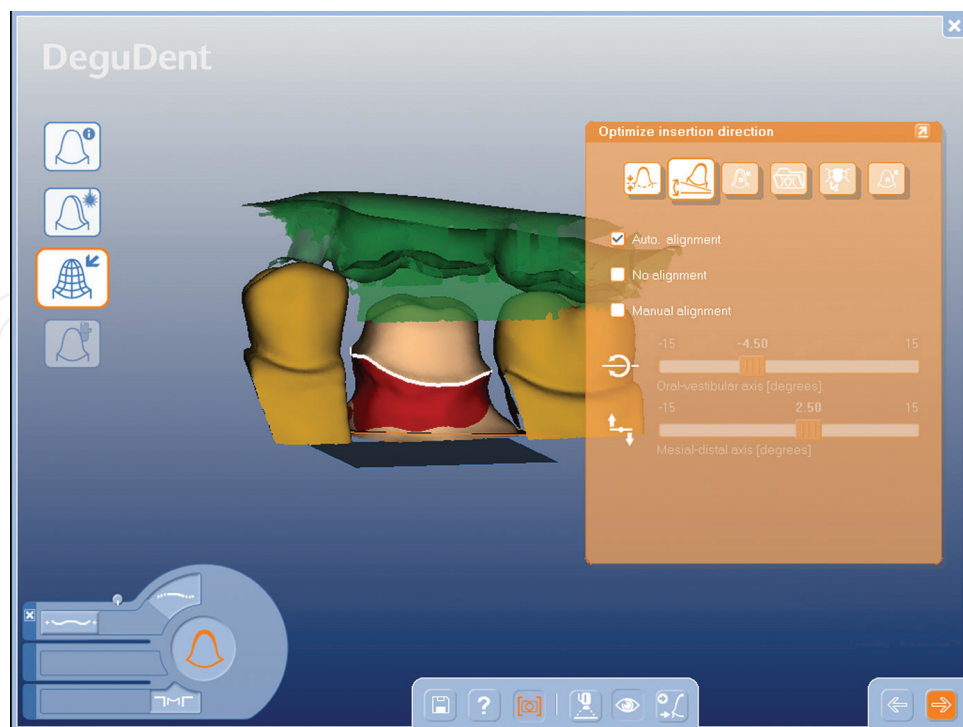
The master die, the antagonist stone cast, and bite-registration were scanned using the Cercon Eye scanner (Degudent, Hanau, Germany) (**Figure 1**).

Scanned data were computed, and frameworks for all-ceramic crowns were designed using Cercon Art 3.2 software (Degudent, Hanau, Germany). Three different framework designs were chosen: first, a 0.6-mm-thick framework was prepared, second, a cutback design was prepared as same as that for metal-ceramic crowns, in order to obtain a uniform, adequate thickness for the veneering porcelain, and third, a buccal reduction from the anatomic framework, for esthetic purposes (**Figures 2–4**).

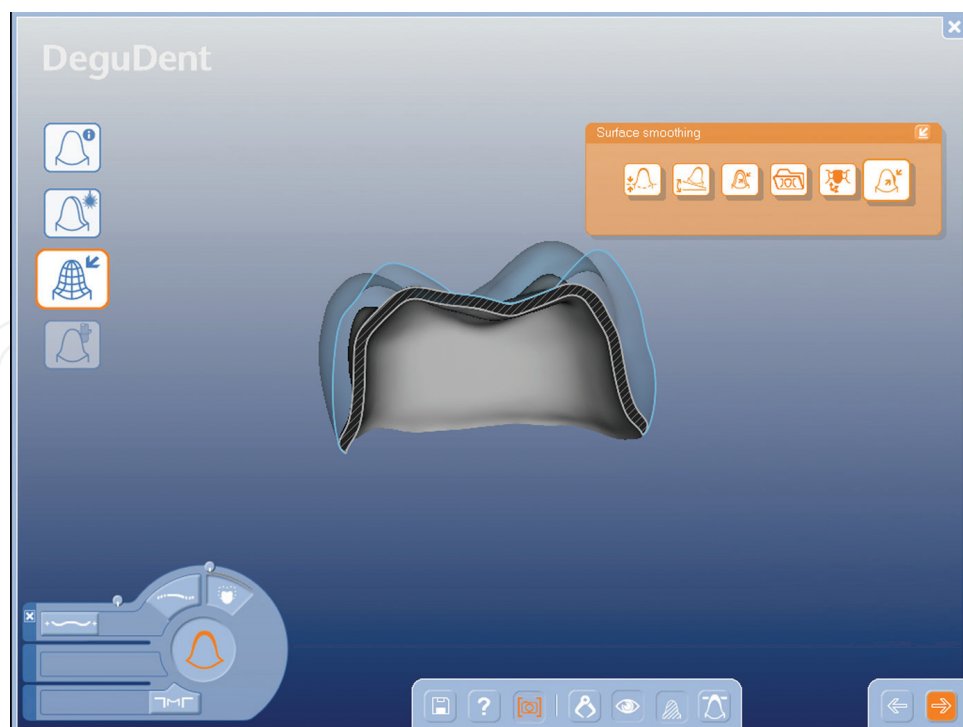
All steps indicated from the manufacturer have been completed for each type of framework design. Cercon Art allows obtaining different designs for lateral single crowns frameworks due to the continuous improvements of the software. Hence, the design of the framework and the future veneer can be controlled.

Cercon Art soft allows also the possibility to scan the bite-registration and therefore an improved digital design of the framework (**Figures 5 and 6**), concerning the control of the veneer thickness in case of the cutback design and also of the contacts with the antagonists in case of a buccal veneering.

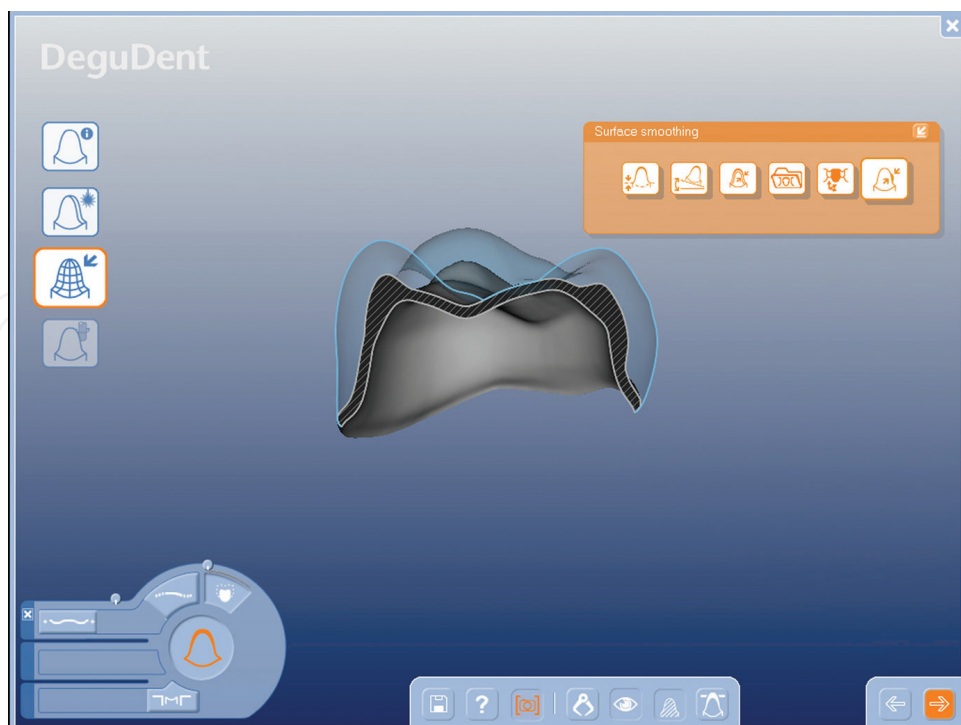
In case of the uniform framework thickness, the veneer design can be also digitized and have an overview of the finished restoration. Beginning from the final morphology of the restoration, the cutback design provides a uniform thickness of the veneer and a digital control of the



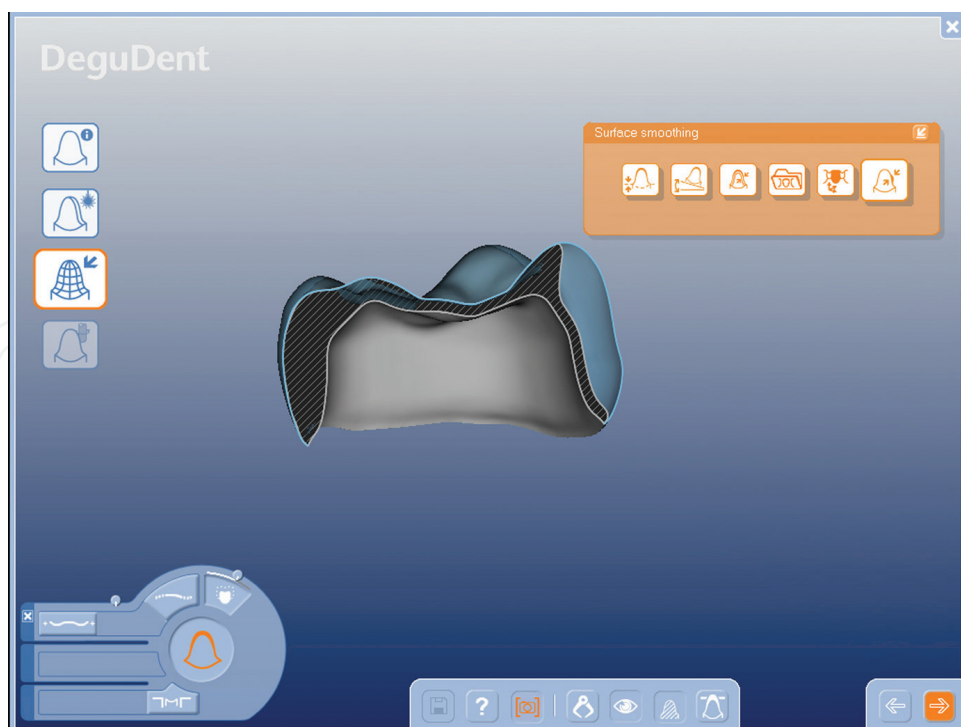
**Figure 1.** Scanned preparation, adjacent teeth, antagonists, and occlusion.



**Figure 2.** Uniform thickness of zirconia framework and digital control of the veneer design.



**Figure 3.** Uniform thickness of veneering ceramic when the framework is obtained with cutback design.



**Figure 4.** Full anatomic contour of the zirconia framework, with buccal reduction of the veneer.





**Figure 5.** Zirconia anatomical framework design.



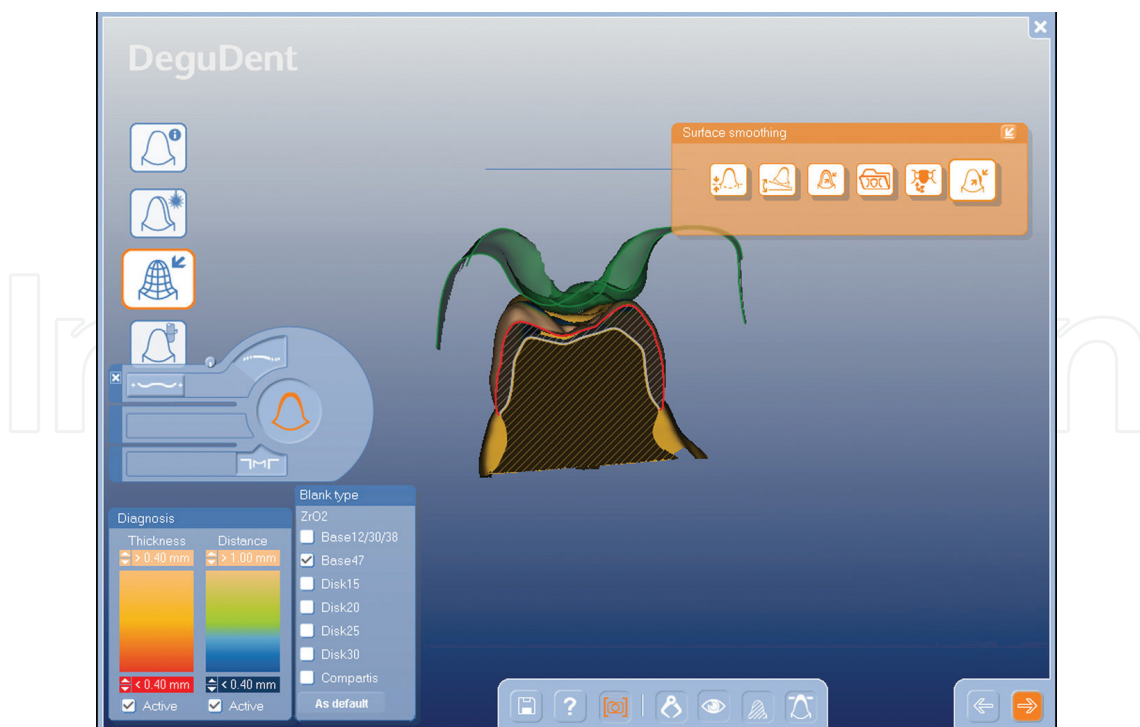
**Figure 6.** Zirconia anatomical framework design after optimization of the contact points with the adjacent teeth and antagonists.

framework thickness. The vestibular veneer became possible also due bite registration, allowing accurate and individualized modeling of the occlusal morphology. A facility of the soft is to have diagnostic tools, regarding thicknesses and distances, which allow a better control of the design (Figure 7).

Literature concerning the clinical performance of all-ceramic systems is inconclusive regarding the relative performance of different materials and physical configurations. Proper studies investigated modified designs and showed the benefits of additional porcelain support compared with a standard design by improving the reliability of all-ceramic crown systems [14]. Clinical studies on zirconia fixed partial dentures with anatomic framework design showed promising survival rates [15].

Improper framework designs cause an inadequate substrate for the veneering material and also its inadequate thickness. The improvement of the framework design, by creating an appropriate support, allows a proper thickness of the veneer proved to reduce the chipping rates [16]. The cutback design of the zirconia framework for all-ceramic crowns is thus a promising way to reduce veneer chipping failures [10].

The design of the substructure, especially the zirconia frameworks, provided different support of the veneering. Veneering porcelain with improved strength and fracture toughness may be one aspect to reduce chipping effects, but only with the change in the design of the supporting substructure, the number of chipping should be effectively reduced [17].



**Figure 7.** Diagnostic tools of the soft regarding thicknesses and distances.



Various influencing factors have been reported, such as the support and thickness of the veneer, the morphology of the circular finishing line, the adhesive forces between substructure and veneering, the mismatch of coefficients of thermal expansion, or the firing protocol during the veneering process [17–20].

Optimization of the zirconia substructure design has been proven as a considerable factor in reducing chipping failures, and coping modifications are still a topic of current investigations [14, 21].

Experiments using finite element analysis may help to predict the fracture behavior of specific material combinations, but failure types and patterns are notably influenced by clinical variables, such as an individual crown design with its occlusal variations, the patients chewing behavior, and functioning in an oral environment [22, 23].

### 3. Simulation methods applied in all-ceramic bilayered crowns

For restoring teeth with single crowns, yttria-stabilized zirconia cores veneered with dental porcelains are highly esthetic alternatives to conventional metal-ceramic crowns. Zirconia ceramics can be processed only with computer-aided design/computer-aided manufacturing technologies, and its properties were proven under *in vitro* and *in vivo* conditions over the past years [24–27].

The application of full-contour zirconia restorations is currently discussed as alternative to commonly veneered restorations [27–29].

By applying veneering materials, esthetically superior results can be achieved, but these materials have mechanical properties inferior to those of the frameworks. Because the veneering glass ceramic is the weakest part in this system, clinically observed failures are mainly restricted to the veneer layer [30].

Failure of all-ceramic dental restorations is predominately caused by cohesive fractures of the glass ceramic veneering material [31].

Failure rates were reported due to this “chipping” called failure mode. Some investigations showed an influence of the firing process of the glass ceramic veneering and the difference in the coefficients of thermal expansion [32–34].

Another important factor influencing the chipping behavior of veneered zirconia restorations is the framework design. An anatomical shape of the framework results in a low and nearly constant veneering thickness. This design is considered to prevent chipping in contrast to a thin framework with a thick and irregularly shaped veneering [35, 17].

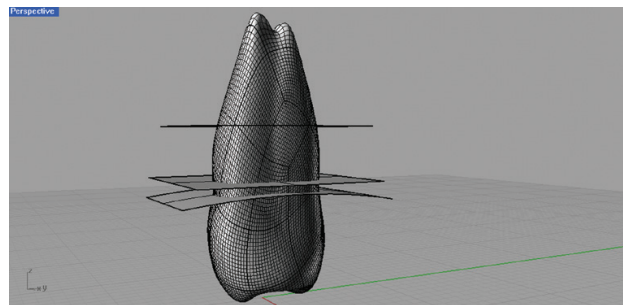
Mechanical stresses that occur during mastication can also be strongly affected by the framework design [36].

Laboratory tests such as finite element analysis may help to predict fracture behavior of specific material combinations. It was demonstrated that failure types and patterns are mainly

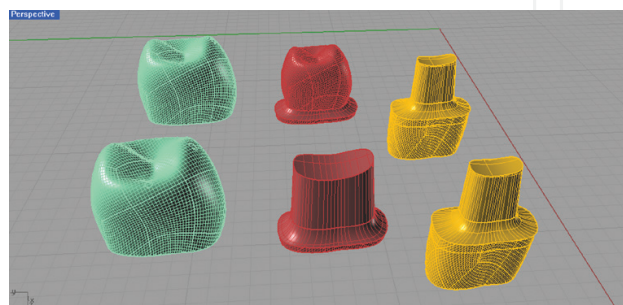
influenced by clinically determined reasons, such as preparation design, internal and marginal fit, cement thickness, and also technological reasons, like the individual crowns design with occlusal morphology and therefore different effects on stress distribution. Simulations imitating clinical situations during fatigue and thermal variations may help to study the behavior of the restorations under clinically approximated conditions. Failures resulted after simulation should be combined with clinically observed failures. Fractographic methods provide additional information to describe ceramic failures [26].

FEA can be used to evaluate the effect of core design on stress distribution in all-ceramic crowns [37]. A maxillary first premolar tooth was used as primary 3D model. The design of the prepared tooth was according to the clinical rules listed as follows: occlusal 2 mm reduction, 0.8 mm deep reduction chamfer margin, 6° convergence angle. The nonparametric modeling software (Blender 2.57b) was used to obtain the tooth shape. The collected data were used to construct three dimensional models using Rhinoceros (McNeel North America) Nonuniform Rational B-Splines (NURBS) modeling program (**Figure 8**).

A digital model of the bilayer crown was designed to occupy the space between the original tooth form and the prepared tooth form. Two different framework designs were constructed: model 1—a coping with a constant framework thickness of 0.6 mm and model 2—an anatomically modified shaped cusp-supporting framework with a constant veneering thickness (**Figure 9**). The geometric models were imported in the finite element analysis software Ansys and meshed using curvature-based mesh software. Finite element calculations were carried out.



**Figure 8.** 3D model of the premolar.



**Figure 9.** Tooth preparations and overlying restorations.

For the structural simulations, the Young's modulus and Poisson's ratio were entered into the computer soft: Young's modulus (GPa): 18 for dentin, 64 for veneering ceramics, and 205 for zirconia; Poisson's ratio 0.27 for dentin, 0.21 for veneering ceramics, and 0.31 for zirconia. Five loading areas were defined on the occlusal surface, each with a diameter of 0.5 mm. A total force of 600 N was applied as pressure load normal to the surface in each point. The bottom of the teeth models was constrained in all directions, for all simulations.

A static structural analysis was performed, in order to generate stress distribution for all designs taken into the study. Maximal equivalent stresses were recorded in the tooth structures and in the restorations for all preparation types (**Figures 10 and 11**).

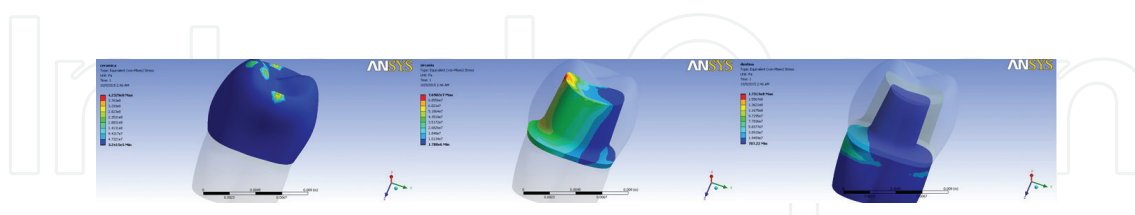
For all cases, the stress values were higher in the veneers. Regarding the distribution, in the veneers, stresses were located around the contact areas with the antagonists. In the frameworks, maximal equivalent stress values were higher for the cutback design, but for interpretation, they have to be correlated with the thicknesses of the frameworks. The outer geometry of all-ceramic restorations is strongly defined by anatomical and physiological circumstances, and therefore, the thickness is variable.

However, a modification of the framework design does not affect the outer shape and thickness of the restoration which means that a thicker framework automatically results in a thinner veneering and vice versa.

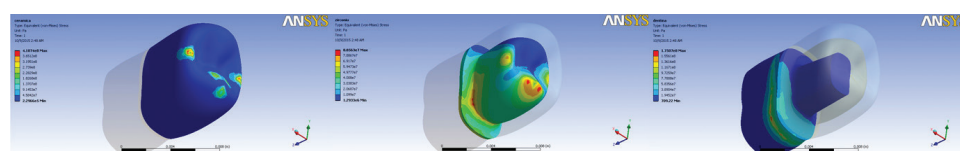
Therefore, the models were created with constant outer shape, where the framework thickness was chosen to be either constant or anatomically optimized [38].

Different studies indicated core and veneer designs that minimize tensile loading of porcelain. They investigated the effect of differential coping designs on the stress distribution of all-ceramic crowns under varying loads. The hypothesis of whether a customized coping design could reduce the stress on veneers is partially accepted [39].

Mechanical testing of anatomic core design modification revealed a significant increase in the reliability of the coping design and resulted in reduced chip sizes in the veneer porcelain [40].



**Figure 10.** Von Mises equivalent stress distribution in model 1.



**Figure 11.** Von Mises equivalent stress distribution in model 2.

Based on the results, chipping seems to be a phenomenon, which is not limited to zirconia restorations, but to the design of the substructure. The chipping failures of all-ceramic zirconia crowns can be significantly reduced in number and surface by fabricating optimized zirconia substructures. These have to provide occlusal support and similar layer thickness for the veneering porcelain [17].

The results showed that not only the substructure design but also the application technique and type of veneering material influenced the chipping behavior of zirconia molar crowns [41].

Some authors investigated the influence of framework design and framework material on the stress distribution in a single tooth restoration, also under different mastication scenarios using the finite element method. The results presented here show that a cusp-supporting framework design can significantly decrease maximum tensile stresses in the veneering material of single crowns. Therefore, it can be expected that such a design could decrease the risk of chipping in all-ceramic restorations in vivo [38].

Use of controlled veneer application techniques, such as the press technique, as well as minimizing stress during the firing conditions may constitute one possibility to reduce cracking and chipping failures. However, only in combination with an anatomically reduced substructure design and a constant layer of the veneering porcelain, the number and dimension of failures (chippings, cracks) are likely to be effectively reduced [41].

#### **4. Simulation methods applied in monolithic ceramic crowns**

Zirconia is considered a proper material for posterior teeth restoration, because of the excellent esthetic quality, biocompatibility, and mechanical properties. Thus, zirconia is getting attention to replace existing ceramic systems. Processing of zirconia is closely linked to the development of CAD/CAM systems [42–44]. CAD/CAM technology has been increasingly used to fabricate dental crowns in recent years. It resulted in new restorative materials that would otherwise have been infeasible to use in the dental market, like Yttria-Stabilized Tetragonal Zirconia Polycrystals (Y-TZP). Recently, the introduction of new computerized milling technologies and new zirconia made it possible to manufacture full-contour zirconia crowns with higher strength [45–47]. Several manufacturers have improved the aesthetics of the zirconia materials mainly by reducing the opacity of the material and by addition of coloring pigments. It might also be assumed that, by omitting the veneering, a more solid framework can be made and a conservative preparation similar to full-cast metal-alloy restorations can be performed [48].

Monolithic crowns offer advantages compared to bilayered crowns like reduced production time and related improved cost effectiveness. Because crown preparation involves traumatization to the vital tooth, eliminating the veneering material in monolithic crowns allows to achieve minimally invasive preparations and subsequent restorations [49–51].

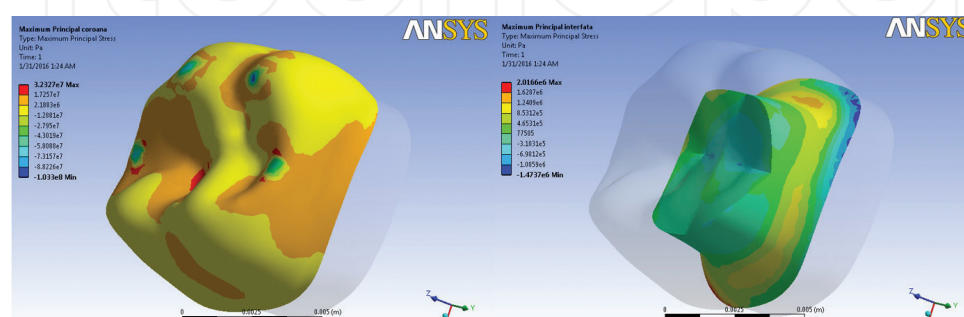
Finite element analysis is a specific method for stress analyses. Since it was developed, it has been a popular option to analyze stresses in engineering field. In dentistry, FEA has been



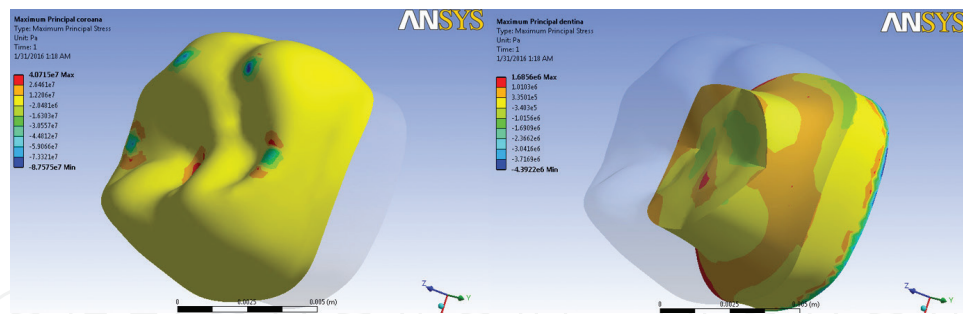
introduced to study stress distributions in the teeth structures and all kind of restorations [52–54]. Even computer-controlled techniques are used in producing dental crowns in order to improve the accuracy during the manufacturing process, not enough studies have been conducted on stresses in esthetic monolithic crowns regarding the load values. Therefore, it is advisable to compare the stresses in anatomic contour zirconia crown to that of glass ceramic crown regarding the load values, from biomechanical point of view [55]. For the experimental analyses, first upper molars were chosen in order to simulate the biomechanical behavior of the teeth restored with complete esthetic monolithic crowns made of yttria-stabilized tetragonal zirconia polycrystals and glass ceramic. The prepared dies were designed with a chamfer finishing line and an 6° occlusal convergence angle of the axial walls.

Geometric models of monolithic crowns were designed to occupy the space between the original obtained tooth form and the modeled prepared tooth form. At first, a nonparametric modeling software (Blender 2.57b) was used to obtain the 3D tooth shapes. The collected data were used to construct 3D models using Rhinoceros modeling program (McNeel North America) (Nonuniform Rational B-Splines). These were imported in the FEA software ANSYS; meshed and finite element calculations were carried out. In order to simulate stress distribution and calculate stress values, the Young's modulus and Poisson's ratio 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. Five loading areas were defined on the occlusal surface, in order to simulate physiological mastication behavior. Each defined loading area had a diameter of 0.5 mm. A total force between 200 N, respective 800 N was allocated to these areas as pressure load normal to the surface in each point. For all simulations, the bottom of the abutment teeth models was constrained in all directions. A static structural analysis was performed using the computer-aided engineering software, to calculate stress values and highlight stress distribution. First principal stresses were recorded in the tooth structures and in the restorations for all load values and all geometries. Stresses were calculated in the crowns for both materials and in the teeth structures, under different load values (**Figures 12 and 13**).

Between the materials, the highest stresses were recorded in glass ceramic, followed by zirconia. In the dentin, the lowest stresses were recorded for the teeth restored with glass ceramic, followed by zirconia. Compared to the tensile strength of the materials, 745 MPa for zirconia,



**Figure 12.** First principal stress distribution in the zirconia crowns and subjacent dentin (for 200 N load).



**Figure 13.** First principal stress distribution in the glass ceramic crowns and subjacent dentin (for 200 N load).

and 48.8 MPa for glass ceramic, the maximal principal stresses in the crowns exceed them for 600 N and 800 N load for zirconia crowns, respective for 400 N, 600 N, and 800 N load for glass ceramic crowns. The maximal principal stresses in the crowns do not exceed the strength of the materials in case of 200 N load for both studied materials. For glass ceramic at a load of 400 N, maximal principal stresses exceed the tensile strength value of the material.

Regarding stress distribution in the crowns, high stresses are concentrated around the contact areas with the antagonists, and they are larger for the zirconia crowns. In the dentin for molars, high stresses were distributed around the shoulder, and under the preparation line for all type of restorations.

The material is important to withstand increased loads which occur during functions. Reported loads during normal function in vivo vary considerably. It is not stated how these loads should be replicated in vitro. Some authors use lower loads, 100–200 N, others use loads in the range of 500–800 N [56].

According to the literature data [57] that the tensile strengths of dentin ranged from 44.4 to 97.8 MPa, no harmful effects occur in hard teeth structures, because in all cases, first principal stresses in dentin are much lower.

When compared with some reported clinical failure rates, it can be stated that the theoretical predictions showed relevant quantitative values for some materials. Even though there are some differences in assumptions between clinical and theoretical models, they can be justified and an even more accurate prediction tool for single crowns may be developed by incorporating better mechanical models in the future [58].

## 5. Conclusions and perspectives

In current practice, frameworks of all-ceramic restorations are obtained by milling even thickness copies, rather than using a scientific-based design. The recent possibility of the softs of the CAD/CAM systems to scan the bite-registration allows achieving an improved digital design for the framework, through the control of the final veneer thickness in case of cutback design and of the contacts with the antagonists in case of buccal veneering.



The effect of zirconia copings design on the resistance to load in posterior crowns in order to prevent “chipping” is very important. Finite element analyses provide a biomechanical explanation of the clinical behavior of different all-ceramic bilayer crowns. A cusp-supporting design reduces maximum stresses in the framework, but these have to be correlated also with the thickness of the framework.

The biomechanical behavior of ceramic monolithic crowns for the posterior areas can be assessed using finite element analyses. The material is important to withstand increased loads which occur during functions.

Stress values and distribution results can provide design guidelines for new and varied esthetic crowns, in order to withstand functional loads in the posterior areas. The development of well-designed experiments could be useful to help to predict clinical survival of these new all-ceramic restorative techniques and materials. The experiments have to be conducted and interpreted reported to the brittle behavior of ceramic systems. Varied simulation methods are promising to assess the biomechanical behavior of all-ceramic systems and first principal stress criterion is an alternative for ceramic materials investigations.

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