FMUC FACULDADE DE MEDICINA
UNIVERSIDADE DE COIMBRA

Ceramic Onlay: Influence Of The Deep Margin Elevation Technique On Stress Distribution - A Finite Element Analysis

Fernando André Moreira Rodrigues

Supervisor: Fernando Guerra DMD, MSc, PhD

Co-supervisor: Rui Isidro Falacho DMD, MSc

Integrated Master in Dentistry

Faculty of Medicine - University of Coimbra

Coimbra, 2016

Ceramic Onlay: Influence of the Deep Margin Elevation Technique on Stress Distribution - A Finite Element Analysis

Rodrigues, F*, Falacho, RI**, Guerra, F***

** Student of the 5th year of the Integrated Master in Dentistry of the Faculty of Medicine of Coimbra University*

*** DMD, MSc, Assistant Professor of the Department of Fixed Prosthodontics of the Faculty of Medicine of Coimbra University*

**** DMD, MSc, PhD, Professor and Head of the Department of Fixed Prosthodontics of the Faculty of Medicine of Coimbra University*

Address:
Área da Medicina Dentária da Faculdade de Medicina da Universidade de Coimbra
Avenida Bissaya Barreto, Bloco de Celas
3000-075 Coimbra

Phone number: +351 239484183 Fax: +351 239402910

Email address: fernando_rodrigues_5@hotmail.com

Index

1. Abstract

Objectives: to compare two types of approaches in the restoration of cavities with subgingival margins in the posterior region, one with the deep margin elevation technique and one in which this technique was not used, aiming to evaluate the distribution of dental forces work and fulcrum points that can cause premature failure in the restorative outcome, by means of finite element analysis (FEA).

Materials and methods: A 3D model of the maxillary first premolar was modelled and used. Preparation consisted in MOD cavities with subgingival margins. The deep margin elevation technique was applied in one of the models and not in the other. Both models were restored with a ceramic onlay. Increasing loads of 250N (low), 500N (maximum) and 800N (excessive) were applied in different sites, at different times. First, the loads were applied in the internal side of the buccal cusp, at 135-degree angle to the long axis of the tooth (eccentric force). Secondly, the increasing occlusal loads were applied in the center of the occlusal surface, at an 11-degree angle to the long axis of the tooth (concentric force). The object used for the load application was a stainless steel sphere (6 mm in diameter). The respective stress distributions in the onlay and in the interface were analysed using 3D models.

Results: the stress distribution was practically the same in the model with deep margin elevation technique and in the model without deep margin elevation technique, when a 200N, 500N and 800N load was applied in the centre of the occlusal surface, at an 11-degree angle incidence (concentric force). When a 200N and 500N load was applied in the internal surface of the buccal cusp, at a 45-degree angle incidence (eccentric force), the difference between the stress distribution of both models wasn't significant. With the application of a 800N load in the internal surface of the buccal cusp at a 45-degree angle incidence, the difference between the stress distribution of both models was significant, with a higher stress accumulation in the model without the deep margin elevation technique.

Conclusions: When high eccentric forces are applied to teeth with subgingival margins restored with an all-ceramic onlays, the deep margin elevation technique seems biomechanically beneficial.

2. Resumo

Objectivos: Comparar, por meio da análise de elementos finitos (FEA), dois tipos de abordagens na restauração de cavidades com margens infragengivais na região posterior, uma com utilização da técnica de elevação da margem e outra em que esta técnica não foi utilizada, com o objetivo de avaliar a distribuição das cargas oclusais e identificar os pontos de fulcro que podem causar a falha prematura no resultado restaurador.

Materiais e métodos: Um modelo 3D do primeiro pré-molar superior foi modelado e utilizado. A preparação consistiu em cavidades MOD com margens subgengivais. A técnica de elevação da margem foi aplicada num dos modelos e não foi aplicada no outro. Ambos os modelos foram restaurados com um onlay cerâmico. Cargas crescentes de 250N (baixa), 500N (máxima) e 800N (excessiva) foram aplicadas em locais diferentes, em momentos diferentes. Primeiro, as cargas foram aplicadas na vertente interna da cúspide vestibular, com uma incidência de 45 graus relativamente ao longo eixo do dente (força excêntrica). Em segundo lugar, as cargas oclusais crescentes foram aplicadas no centro da superfície oclusal, a uma incidência de 11 graus relativamente ao longo eixo do dente (força concêntrica). O objeto usado para a aplicação de carga foi uma esfera de aço inoxidável (6 mm de diâmetro). As respectivas distribuições de stress no onlay e na interface foram analisadas utilizando modelos 3D.

Resultados: A distribuição de stress foi praticamente a mesma no modelo onde foi aplicada a técnica de elevação da margem e no modelo em que não foi aplicada a técnica de elevação da margem, com cargas de 200N, 500N e 800N no centro da superfície oclusal, com uma incidência de 11 graus (força concêntrica). Quando for aplicada uma carga de 200N e 500N na vertente interna da cúspide vestibular com uma incidência de 45 graus (força excêntrica), a diferença entre a distribuição de stress de ambos os modelos não foi significativa. Com a aplicação de uma carga de 800N na vertente interna da cúspide vestibular, com uma incidência de 45 graus, a diferença entre a distribuição de stress de ambos os modelos foi significativa, sendo a acumulação de stress maior no modelo em que não se aplicou a técnica de elevação da margem.

Conclusions: Quando são aplicadas elevadas forças excêntricas a dentes com margens subgengivais restaurados com onlays cerâmicos, a aplicação da técnica de elevação da margem parece ser benéfica em termos biomecânicos.

3. Introduction

Dentistry took advantage from the terrific evolution in technology, techniques, and materials(1). The constant appearance of new tools and restorative materials, such as composites and ceramics, exposed aesthetic and functional restorative needs not only for anterior teeth as well as for posterior teeth(2). The alternatives to restore teeth have increased, mostly because of the patient demand for more biomimetic restorations (3-5), with an incresing importance of the aesthethic field in the dental treatment among patients (4, 6, 7). The challenge became to merge the mechanical requirements, resistance and wear to the masticatory forces of the molars and pre-molars, with materials that recover the naturalness of the teeth(2). One response to this challenge are the adhesive restorations.

The use of indirect adhesive restorations has rising bibliographic support and it became a key option for rehabilitation in the posterior sector. However, the literature is scarce in comparative studies of different methodologies of tooth preparation for the execution of such restorations.

Thus, the objective of this study is to compare two types of ceramic onlay cavity designs in the posterior region, one with the use of the deep margin elevation technique and one in which this technique was not used, in terms of stress distribuition and fulcrum points that can cause premature failure in rehabilitation.

1. Indirect restorations

The indirect restorations are indicated in large cavities of posterior teeth, when the occlusal isthmus is bigger than half of the intercuspal distance or when the preparation comprises one or more cuspids(2).

The preparations for indirect restorations can be classified as:

- Inlay (completely intracoronal; no cusp is covered)
- Onlay (at least one cusp is covered)
- Overlay (all cusps are covered)
- Endocrown (more actual; for teeth with great coronal structure loss; with a cervical projection to the pulpar chamber)

This kind of restorations can recover aesthetics and strength of the posterior teeth, and consist in more conservative alternatives when compared to total crowns(2, 8). Apart from their excellent optical properties and high degree of biocompatibility, which allow them to restore biomechanical integrity, structural and aesthetics to the teeth(7), other advantages described in the literature are their ability to achieve optimal proximal contact with the adjacent teeth(7, 9), facilitate the reestablishment of the occlusal anatomy(7) and simplify polishing and finishing(7).

The correlation between degradation of strength with increasing removal of tooth structure is well reported in the literature(1, 9-11), so the objective of the operator while performing a cavity preparation for an indirect restoration, such as a ceramic onlay, is the preservation of dental structure, always bearing a profound knowledge of the restorative materials physical properties(12).

i. Composite vs. Ceramic

The restorative materials used in indirect restorations can be divided into two types: composites and ceramics.

Although recent studies have shown satisfactory results in the realization of indirect restorations using composites, there are some implicit limitations that make ceramic the material of choice in restoring posterior teeth(7). There are several disadvantages of composites described in the literature, particularly when used in direct restorations, among which stand out technique sensitivity regarding the application protocol of adhesive systems(7), moderate color stability(7), polymerization shrinkage(7, 9), brightness loss over the course of time(7).

The polymerization shrinkage can lead to the formation of flaws(7) in the deflection of the cusps or the commitment of the marginal integrity of the restoration(7), which may lead to post-operative sensitivity(7, 9), microleakage(7, 9) and secondary caries(7).

Ceramics come as a material that eliminates some of these disadvantages. The main advantages of ceramic as a restorative material are: excellent aesthetics and color stability(4, 6, 9, 11, 13-15), biocompatibility(4, 6, 9, 11, 13-15), better margin adaptation(6, 13), greater ability to establish interproximal contacts(6), improved wear resistance(4, 6, 9, 15), improved polishing and lowest microleakage(6, 14), enhanced anatomical and functional reconstruction(6), preservation and protection of the remaining tooth structure(6), less polymerization shrinkage (limited to the cement)(4, 6, 16, 17), radiopacity similar to tooth structure(6), coefficient of thermal expansion similar to that of dental structure(4, 9, 11, 14, 15).

Nowadays, the leading ceramic materials are the classic porcelain ceramics, based on feldspar and glass or a metal oxide. Glass gives ceramics an esthetic translucent property, while oxide ceramics provide high-strength. Feldspathic ceramics are fabricated in a powderbased form and can be applied to many different substructure materials. The material can also be formed into a block to be used in a milling unit or can be pressed in a mold to form a restoration. With the addition of various colorants, it can be made to mimic natural enamel shades and is therefore commonly used as a veneer on other less esthetic materials. Glass-ceramics consist of part glass and part crystalline tetrasilicic mica, which makes the material stronger than feldspathic ceramic. Prefabricated blocks of glass-ceramics can be used to mill substructures. Modern oxide ceramics are composed of a metal oxide, mainly either aluminum or zirconia. Glass-infiltrated oxide ceramics are mostly processed in the form of prefabricated, partially fired milling blanks. The strength of this material can be enhanced by increasing the proportion of zirconia, but this also greatly diminishes the esthetic properties. The newest additions to the market are the yttria tetragonal zirconia polycrystal–based (Y-TZP) ceramics, introduced in the 1990s. These have even higher strength and fracture resistance than previous ceramic materials as well as some esthetic properties. Because of this high strength, Y-TZP ceramics are predominantly used to produce crowns and fixed partial dentures (FPDs) (18).

Indirect restoration of posterior teeth using ceramic as restorative material, particularly in the preparation of onlays is indicated in teeth with caries lesions involving at least two walls(6), replacement of impaired large restorations(6), endodontically treated teeth with extensive coronary destruction(6), replacement of metallic restorations for cosmetic reasons(6), cusp fracture(6), extruded or in subocclusion teeth(6), vital teeth with extensive coronary destruction(6).

But, ceramics aren't the perfect material, as they have issues resembling all the others restorative materials. Generally, ceramic restorations fail due to material flexure and subsequent propagation of cracks under cyclic loading(19). This cyclic loading in a wet environment and the consequent propagation of cracks causes the reduction of strength of the ceramic, leading it to failure(1, 10, 20, 21). Fatigue is an importante factor limiting the lifespan of ceramic restorations and consequently represents a prerequisite for valid in vitro testing(10). Static or fatigue load-to-fracture tests should be conducted on adhesively bonded tooth-restaurations specimens with different preparation designs to assess the effects of preparation design on fracture resistance(19). This will allow trhe clarification on which preparation may lead to higher longevity of the restaurations(4). It's very important that the restorative material besides replacing the missing dental structure, also enhances the fracture resistance and improves the marginal seal(14).

Besides having some disadvantages, ceramics are contraindicated in certain situations, particularly in patients suffering from occlusal overload, more specifically in bruxism cases(6, 7), because the high rigidity of the ceramic piece combined with the occlusal overload will lead to a high probability of fracture and will accelerate wear of the opposing tooth(7, 12). This material is also contraindicated in cases where there is no cervical enamel in the cavity(6), the operator can not perform rubber dam isolation(6) or in unmotivated patients with poor oral hygiene(6). It is of uttermost importance that there is cervical enamel in the cavity and more enamel than dentin, as literature afirms that in the long run, fracture resistance of ceramic bonded with resin to enamel is higher than those bonded to dentin(10, 21).

ii. Ceramic onlay

Bearing in mind what was said before, indirect restoration preparations can be classified as inlay, onlay, overlay or endocrown. As this study focuses on onlays, a more in depth approach will be taken to this type of restoration. However, before that, there are some important ideas that must be expounded.

When preparing a cavity for onlays, the biological principles and the mechanical principles must be respected to the maximum. The biological principles can be divided into two: the preservation of pulp vitality and the preservation of the periodontal structures. The higher the preparation depth, the greater the dentin and pulp susceptibility to irritants, so the operator must dominate to the maximum the surgical technique and use cutting instruments of good quality, always with cooling(6). Periodontal health is critical to the success and longevity of any prosthetic rehabilitation treatment. It is then necessary to take extreme caution during preparation and carefully select the location of cervical end(6).

Relatively to biomechanical principles, these are defined by the technical conditions that allow the production of restorations integrated into the dental anatomy of the preparations. The mechanical principles can be divided into five: enough space for restorative materials; shape of the preparation conferring retention, strength and stability; control of the “critical area” (union between dental tissue and restorative material); function and aesthetics(6). However, in the daily clinical practice, the cavities are wider and deeper than the recommended due to the presence of restorations or caries lesions(5). Therefore, as mentioned before, the operator has to preserve sound tooth as much as possible.

iii. The importance of adhesive procedures in ceramic onlays

The introduction of adhesive procedures in the cementation of ceramics, besides allowing their retention, also provides resistance(7, 12, 21), reinforcing the dental structure in a way that the stiffness values of the restaured teeth are near the values of sound teeth(12), and minimizes negative effects like the cusp flexure(12). This happens because the consequences of the adhesive effects are enchanced crown stiffness, cohesive resistance and stress distribuition(12).

Regarding adhesive luting, in cases of posterior teeth with thick ceramic restorations, the operator should choose to use dual polymerization cements, since they combine the chemical activation process and the physical activation process(7). This allows the polymerization reaction to occur in opaque restorations and deep and interior areas of the cavity preparation, areas that light curing can not reach with the proper intensity(7), leading to marginal gaps, inadequate cement polymerization, secondary caries and marginal leakage(6).

iv. "Deep marginal elevation" or "coronal margin relocation" or "proximal box elevation"

When cavity margins overstep the biological width, a crown-lengthening procedure is indicated(17, 22, 23). However, when in the presence of subgingival cervival margins (a more frequent condition), a conservative deep margin elevation with direct composite resin is advised by some(17). This technique allows to lift the deep cervical margin to a visible and accessible level (supregingival)(17, 22-24). Thus, this procedure makes impression taking and luting procedures easier(17, 22).

The thickness of composite in these cases is limited to the minimum needed to bring the preparation margins to a supregingival position(17). This allows to control polymerization and optimize the marginal adaptation, while creating an adequate restoration emergence profile(17, 23).

For a successful application of the deep margin elevation technique, Pascal Magne et al, defend that some steps must be respected(25):

1. A curved matrix should be chosen, because the traditional matrix, in margins located at the CEJ region, normally reproduce an insufficient gingival emergence profile and contour;

2. There must be sufficient tooth structure on lingual and buccal directions, so that there is support for the matrix. Extended elevation in the buccal and lingual directions will generally be restricted by matrix instability and collapse;
3. The matrix height must be reduced to 2 to 3 mm, which will allows it to slip subgingivally and seal the margin more effectively;
4. In teeth that need endodontic treatment, DME technique should be done before the endodontic treatment, so it can benefit from an easier isolation with rubber dam while the root canal therapy is performed;
5. When the matrix is finally placed, there can't be gingival tissue or rubber dam between the margin and matrix;
6. Before bonding, the elimination of the remains and other contamination of the dentin that may have occurred during matrix placement must be carried;
7. Immediate dentin sealing should be done with a three-step etch-and-rinse dentin adhesive, followed by colocation of a composite resin base that will elevate the margin 2mm(one or two increments);
8. For the DME technique, different types of resin can be used (traditional restorative or flowable). Final polymerization must be done with the use of a air blocking gel, like glycerin gel;
9. After the margin is elevated, the excess of resin composite must be eliminated, as well as the excess of adhesive resin;
10. A bitewing radiograph must be done to confirm the absence or the presence of excesses or flaws, before proceeding to the final preparation and impressions.

2. Finite element analysis – what is it and its application in dentistry

In simple words, a finite element analysis is a numerical method for stress analysis(26). It involves a set of computational procedures to calculate the stress and strain in each component, generating a model solution(26).

It was firstly developed by Courant in 1943, using the Ritz method of numerical analysis(27). In 1956, Turner et al created a paper that analysed different mechanical properties, as, for example, the stiffness and deflection of structures with different designs(27). Later, in the 1970s, the advancements in computer technology performed a revolution in many different industries, namely the ones that were related with the fields of energy, the military and the production of new vehicles(27) and it was first applied in dentistry to replace photo elasticity tests(26). The development of technology enabled the finite element analysis to evolve from two-dimensional to three-dimensional modelling(27). The difference between 2D and 3D modelling is that 3D models are more realistic and have a closer to reality representation of the biomechanical interactions in the human anatomy, restorations and implant components. But, in spite of exhibiting these benefits over 2D models, 3D ones have a greater level of difficulty in CAD modeling, solving and output interpretation(26, 28). The decision on forming 2D or 3D models depends on the complexity of the issues that will be approached, the level of accuracy required, applicability of the results and the complexity of the structures involved in the analysis(28).

Finite element analysis produces a mesh, that is like a grid made up of a complex system of nodes(26, 27). The greater the number of nodes, the more refined the mesh. This nodes are placed at a varying density throughout the material and areas that are prone to receiving a large quantity of stress are more presumable to have a greater element density than areas that have no stress(27). The mesh forms to simulate the material and its properties (elastic modulus, Poisson,s ratio and yield strength), and this will define how it reacts to being loaded in a variety of conditions(26, 27).

This method has some advantages when compared with laboratory testing. The main advantages are: variables can be easily changed, simulation can be performed without the need of human material, it offers maximum standardization and it helps to to visualize the point of maximum stress and displacemnt. However, it’s not easy to predict failure in complex designs made of different materials and complex loading varying in relation to time and point of application(26).

Finite element analysis is an important tool that can be used to solve a large number of engineering problems, like heat transfer, fatigue, stress/strain and vibration(27). It is now considered the most theoretically accurate method of solving equations involving compatibility and elasticity. Finite elements are fundamental when analysing bone and tooth failure as these are intimately connected with stress and strain behavior(27).

Finite element analysis are widely used in dentistry.

Relatively to restorative dentistry and endodontics, in 1991, Goel et al used the finite element analysis to study abfraction lesions(27). The behavior of teeth under occlusal loading is one of the major areas of study in this virtual field(27).

Coelho et al applied the finite element analysis to dentine bonding, with the objective of examining whether the microtensile bonding strength values are inversily proportional to the thickness of the layer of the dentine/composite adhesive agent(27).

In endodontics, Subramaniam et al studied the ProTaper® and Profile® nickel-titanium rotatory instruments, comparing their stress distribution and their elasticity(27).

About their use in orthodontics, finite element analysis is applied in four major areas related with the field of the biomechanics: skeletal analysis, the design and construction of orthodontic appliances, the analysis of human growth and the changes in the remodelling bone(27). More recent and more complex is the application of finite element analysis in the study of the geometry of the bracket base(27) and in the manufacturing of templates for the placement of miniscrews(27).

In respect to oral and maxillofacial surgery, Vaigel et al used 3D finite element analysis to study the fixation of an exactly similar mandibular fracture with a multitude of different thicknesses of plate(27).

In orthognathic surgery, the application of the finite element analysis focused in the different osteotomy designs advocated throughout the years. Takahashi et al, evaluated different osteotomy designs and their biomechanical profile(27).

Finally, and maybe the main application of the finite element analysis in dentistry, the dental implantology. Pesqueira et al approached the complexity of the implant/dental interface, namely the stress distribution and the difference in load transfer to the interface between the bone and the implant. Although being a controversial subject, and with no consensus on the ideal method, the finite element analysis contributed to the development of new parts, designs and shapes of implants(27).

4. Materials and Methods

For this study, we have asked the Brazilian Engineer Estevam Barbosa de Las Casas (IEAT Director, School of Engineering, Federal University of Minas Gerais (UFMG), Belo Horizonte MG, Brazil) for a 3D model of the maxillary teeth. Kindly, and in response to our request, a very complete 3D model of the maxillary teeth was sent to us (Image 1).

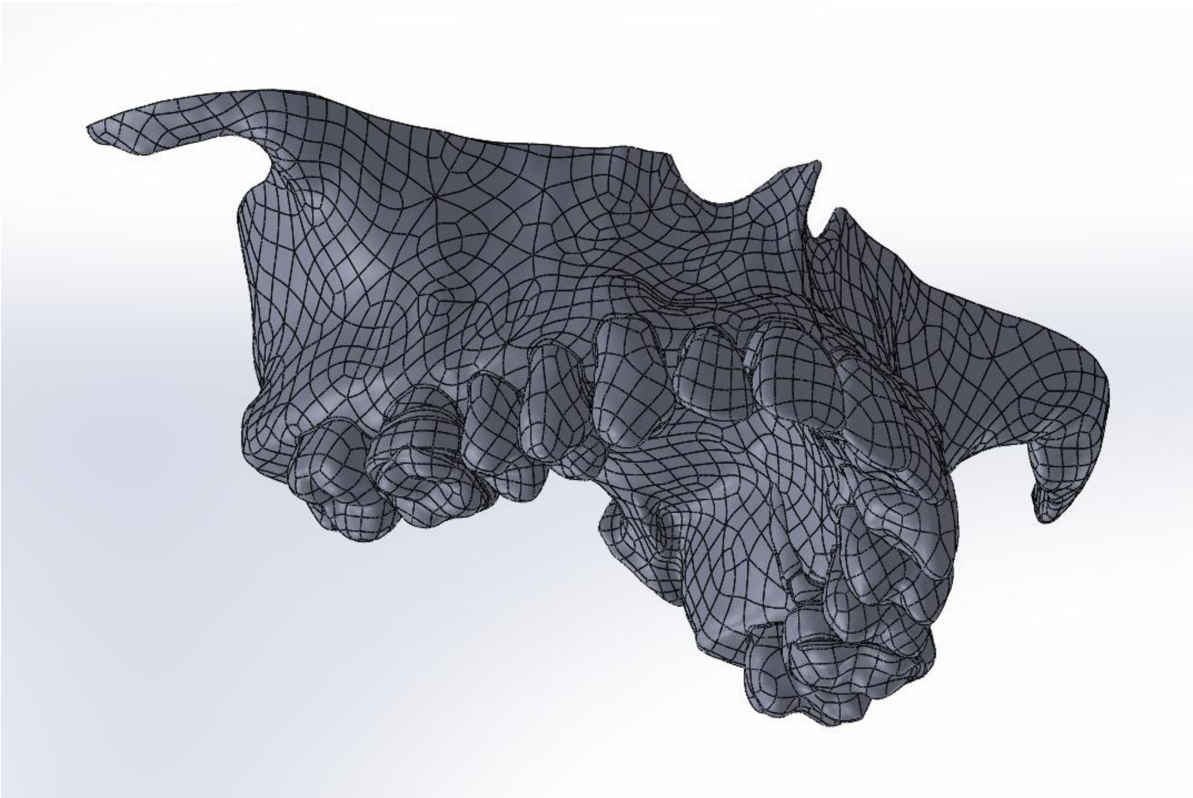

Image 1: model of the maxilla, sent by Engineer Estevam Barbosa de Las Casas

The first maxillary premolar from the left side (24) was chosen, because maxillary premolars have an unfavourable anatomic shape, crown volume and crown/root proportion. These features make these teeth more susceptible to cusp fracture when compared to other posterior teeth(15). To produce the 3D model of what was desired and to execute the finite element analysis, a collaboration was held with Engineer Luis Roseiro (ISEC Professor, Department of Engineering, Polytechnic Institute of Coimbra, Coimbra, Portugal) along with his students Rui Catarrinho, André Oliveira and Júlio Regado at the discipline of Automatic Calculus and Mechanical Systems of the 4th year of the Master’s Degree in Mechanical Engineering.

For the 3D reconstruction of the tooth and for the definition of the tooth components the software SolidWorks (2015 software version, SolidWorks) was used. The original model of the maxilla, in ".STEP" format, was imported to the software and by the process of segmentation (separation of an object of interest from other adjacent anatomical structures in different masks, such as a tooth), the tooth was isolated (Image 2). The tooth components were defined with values obtained in the literature. Those values were: 1,8mm for the occlusal enamel thickness and 3,3mm for the occlusal dentin thickness, 1,4mm for enamel axial thickness and 2,7mm for cervical dentin (Image 3).

(a) (b) (c)

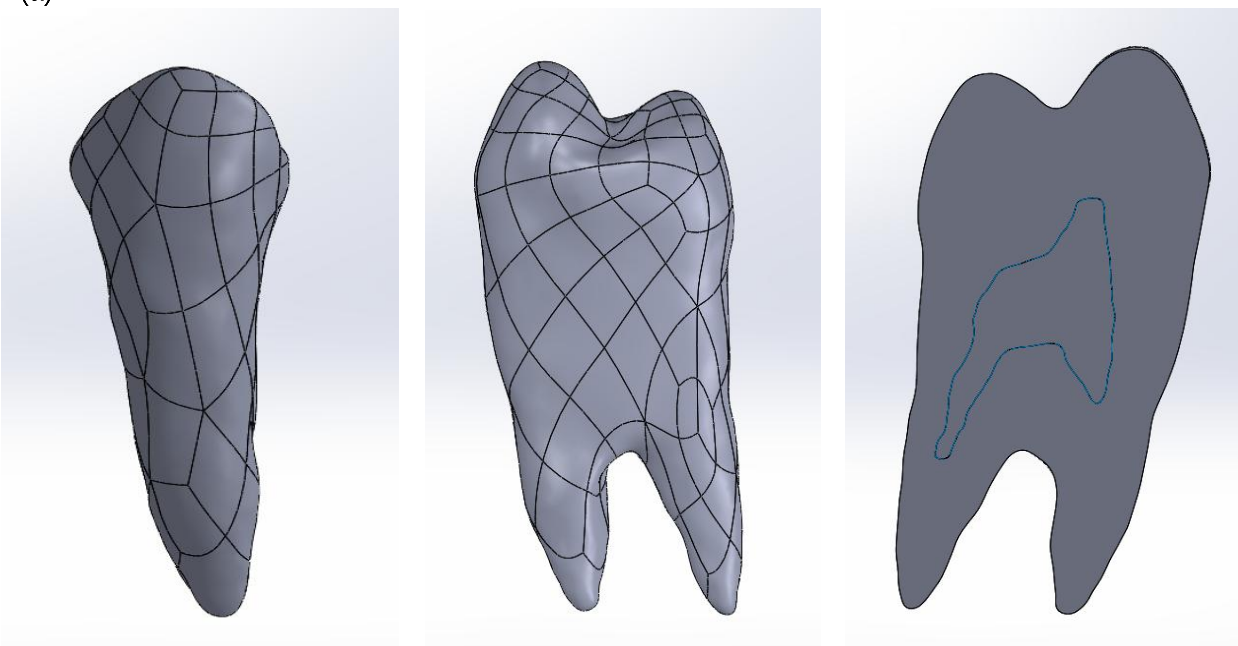

Image 2: tooth selected for the finite element analysis (24), after being isolated and before the definition of the tooth components, on a frontal view (a), on a proximal view (b) and on an internal view (c)

(a) (b) (c)

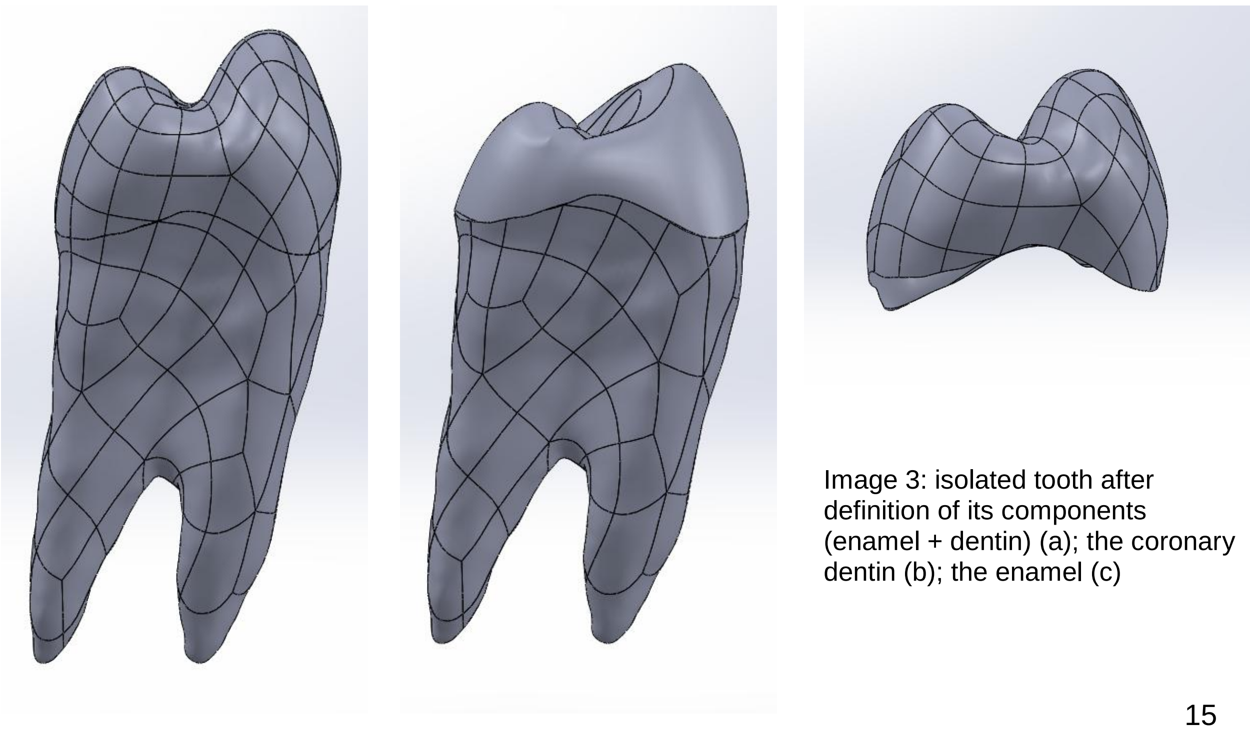

Image 3: isolated tooth after definition of its components (enamel + dentin) (a); the coronary dentin (b); the enamel (c)

The tooth was prepared for MOD onlays with subgingival margins. The preparation measures were: occlusal isthmus with 4,3mm of width. Vestibular wall with 3,5mm of thickness, palatine wall with 2,2mm of thickness, mesial box depth with 3mm, distal box depth with 1,9mm, both the proximal boxes with 4,3mm of width and 2mm of cusp reduction (Image 4).

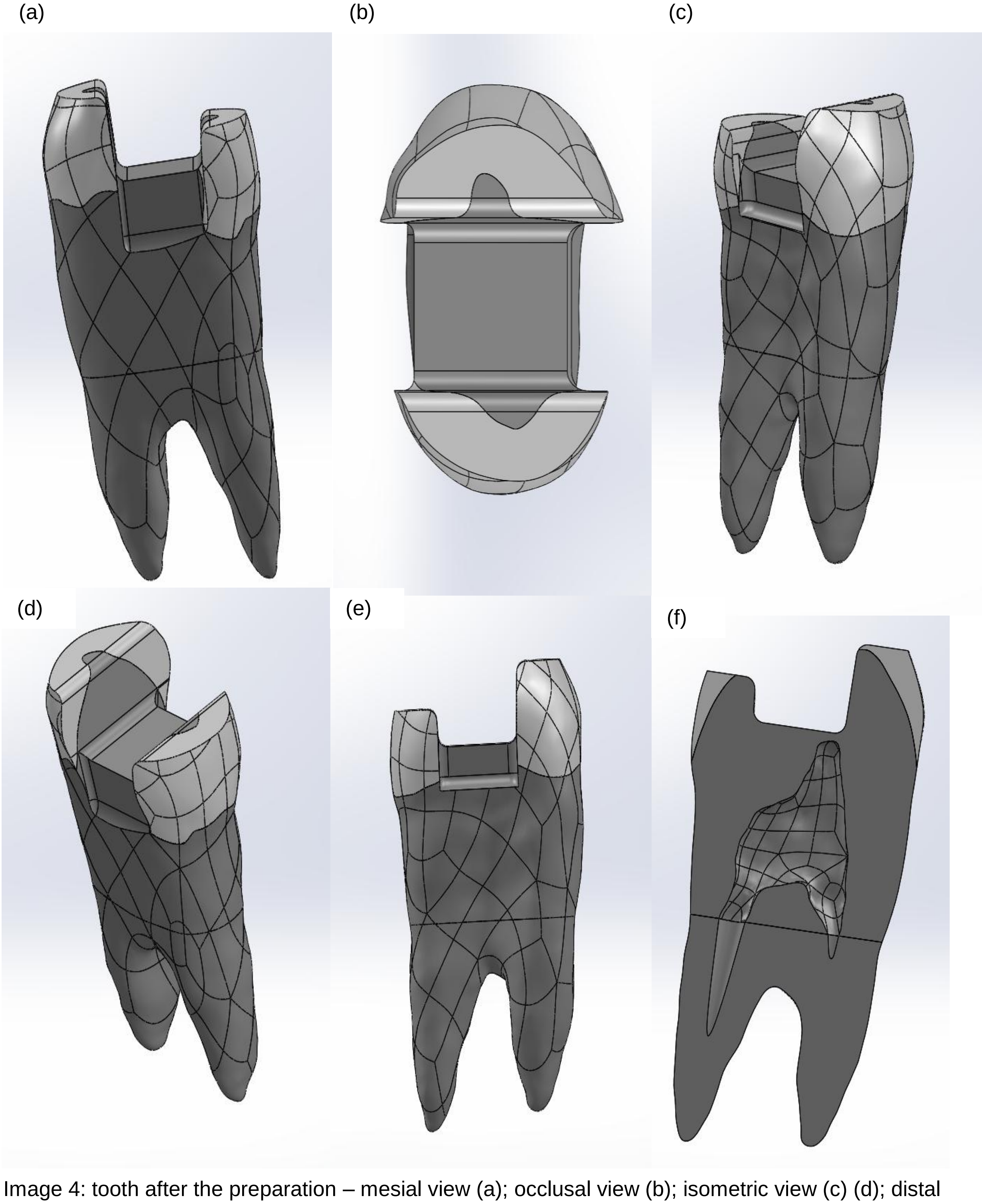

Image 4: tooth after the preparation – mesial view (a); occlusal view (b); isometric view (c) (d); distal view (e); sagittal cut view (f), with the pulp chamber and the root canals

Two models, which focused on the restorative approach (with proximal box elevation or without proximal box elevation), were produced in this study. Model A (Image 5) represented a tooth restored with a proximal box elevation where the deep proximal boxes were filled up with composite resin (IPS Empress Direct, Ivoclar Vivadent) and an all-ceramic onlay (IPS e.max Press, Ivoclar Vivadent) and model B (Image 6) represented the same tooth and cavity preparation restored without the execution of the proximal box elevation technique and with an all-ceramic onlay (IPS e.max Press, Ivoclar Vivadent). Although in model B, the image appears to have a different segment of material in the proximal box, this is only a visual guide for the structure and the entire restoration is a single ceramic block. Model C is the control group, a representation of a sound tooth, as we have seen in Image 3.

(a) (b) (c) (d)

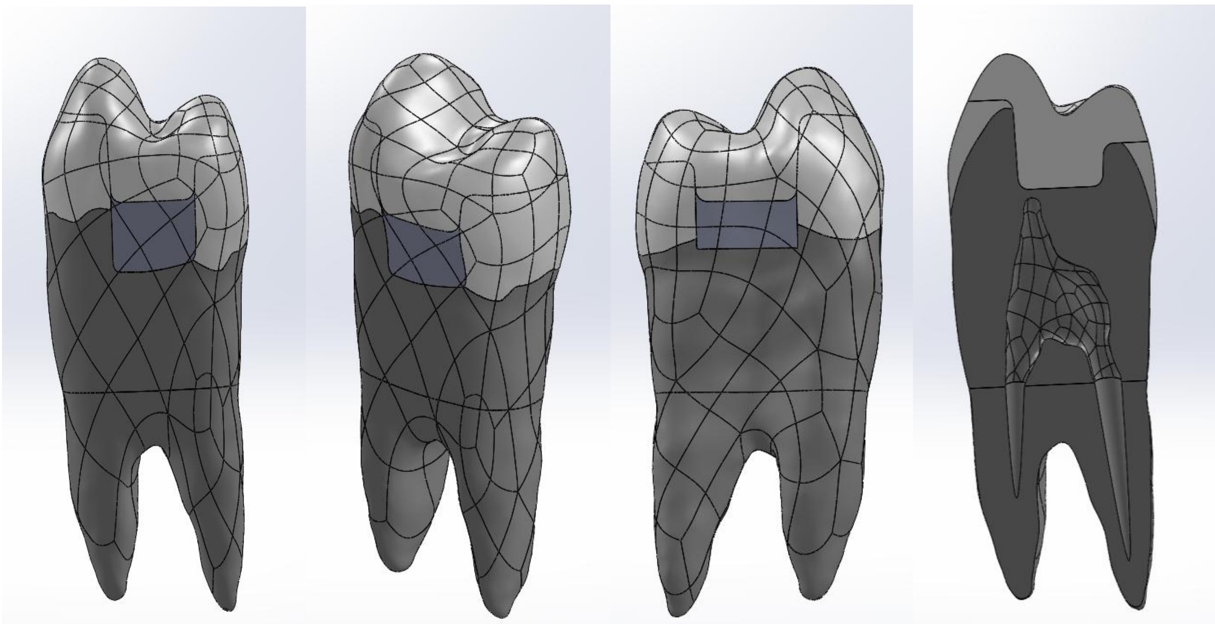

Image 5: representation of model A, the prepared tooth restored with a ceramic onlay after a deep margin elevation technique application, in a mesial view (a), an isometric view (b), a distal view (c) and an internal view after a sagittal cut (d); in blue we can see the filled up box with resin composite, elevating the subgingival proximal box to the occlusal floor of the cavity

To facilitate the production of 3D models for finite element analysis, some assumptions in respect to the 3D geometry and material properties of each part were made. The cementum layer was considered included in the dentin part of the root, because the cementum layer is very thin and its definition would be extremely challenging and would bring limitations, since it requires a high computational capacity. For the same reason, the adhesive interface was not included in the study.

Also the pulp and the periodontal ligament were neglected because of their hyperelastic properties. These hyperelastic elements have been excluded because this is a comparative study between samples in the same conditions and also because it would require a non-linear analysis and this would be quite complex and would take more time than expected (3 to 4 times more).

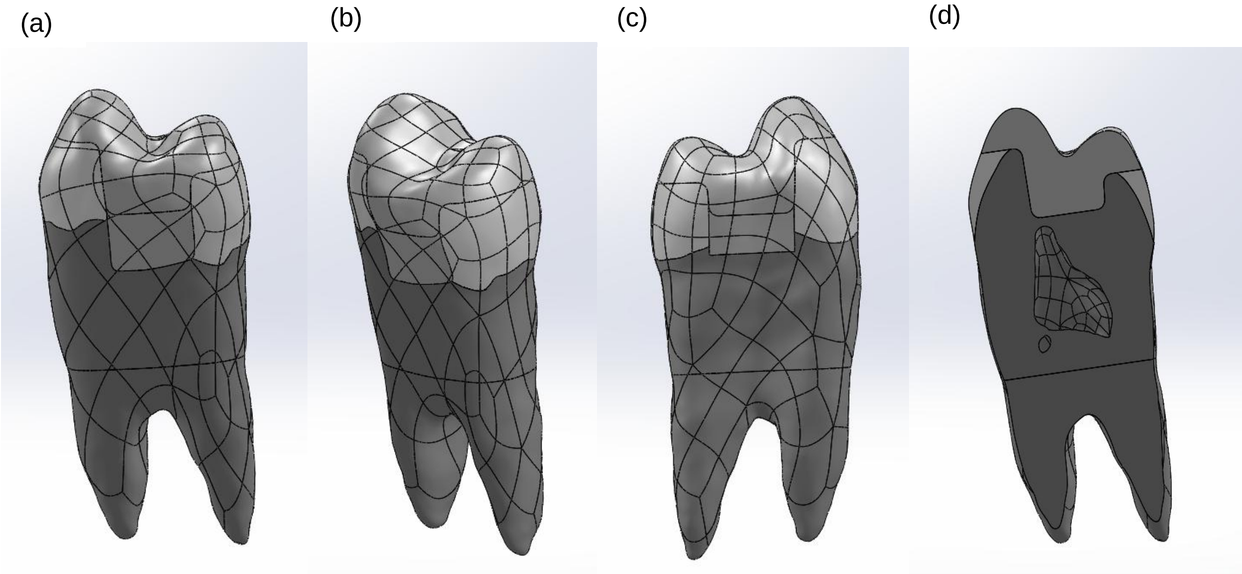

Image 6: representation of model B, the prepared tooth restored with a ceramic onlay without the application of the deep margin elevation technique, in a mesial view (a), an isometric view (b), a distal view (c) and an internal view after a sagittal cut (d)

Simulation of the finite element model, calculation of stress distributions, and processing were performed using SolidWorks software (2015 software version, SolidWorks). The analysis was a linear static analysis, because linear systems are less complex and effective in determining elastic deformation(26).

Appropriate meshing was established based on the convergence test and mesh up of each component, which was set to 0,3 mm (min) and 1,5 mm (max), curvature based mesh (Image 7). A block was used to provide anchoring to the tooth and to simulate the cortical and the cancellous bone (Image 7).

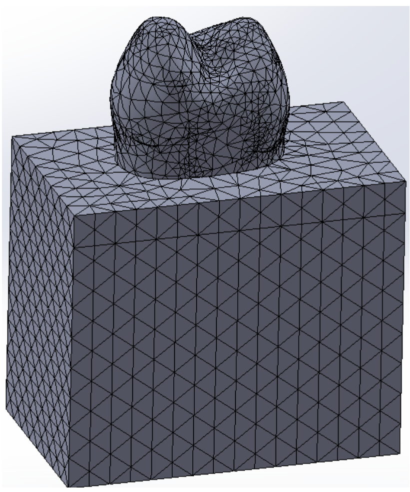

Image 7: a representation of the final mesh; it is also possible see the block were the tooth was anchored and that simulated the cortical and the cancellous bone

Curved tetrahedral solid elements with four nodes and three degrees of freedom were used for stress analysis. The total number of nodes and the total number of elements were different in each model and the values are shown in Table I.

Table I: the total number of nodes and the total number of elements of each model

	Total Nodes	Total Elements
Model A	104744	68510
Model B	95379	62166
Model C	92727	61915

For this study, the three specimens were subjected to occlusal loads of 200N (low), 500N (maximum) and 800N (excessive). These three loads were applied in two different spots, at different times. In one phase, the increasing occlusal loads were applied in the internal side of the buccal cusp, at 45-degree angle to the long axis of the tooth, to study the eccentric forces (Image 8). In the other phase, the increasing occlusal loads were applied in the centre of the occlusal surface, at an 11-degree angle to the long axis of the tooth, to study the concentric forces (Image 9). The object used for the load application was a 6mm stainless steel sphere, digitally modelled (Image 10).

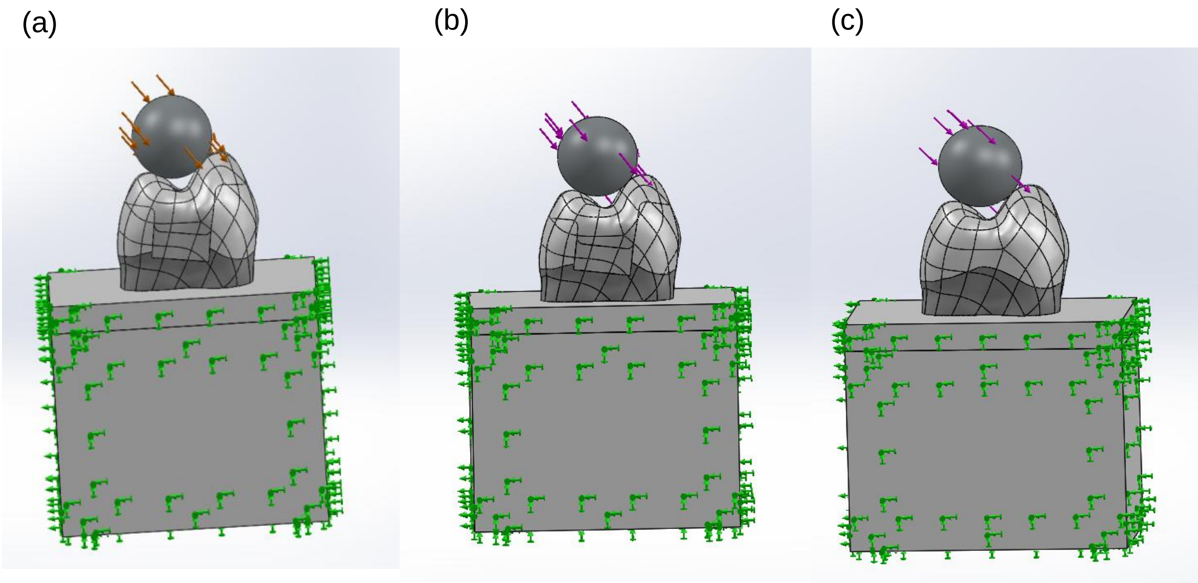

Image 8: application of the loads in the internal side of the buccal cusp, at 135-degree angle to the long axis of the tooth, to study the eccentric forces; the increasing loads of 200N, 500N and 800N were applied to the model A (a), to the model B (b) and to the model C (c)

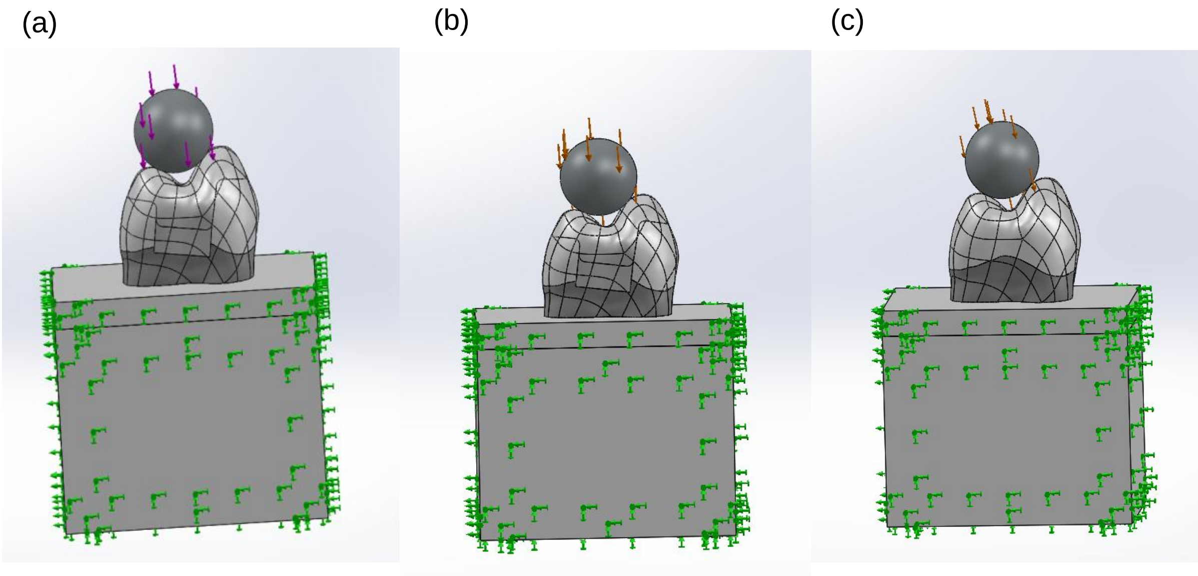

Image 9: application of the loads in the center of the occlusal surface, at an 11-degree angle to the long axis of the tooth, to study the concentric forces; the increasing loads of 200N, 500N and 800N were applied to the model A (a), to the model B (b) and to the model C (c)

The Young's modulus (E) and the Poisson's ratio (V) applied for each component in this study were considered to be isotropic, homogeneous and linear. The mechanical properties of the materials and tooth components are given on Table II. The Young's modulus and the Poisson's ratio used for the ceramic (IPS e.max Press, Ivoclar Vivadent) and for the composite (IPS Empress Direct, Ivoclar, Vivadent) are specific of these materials and brand, and not universal values.

Table II: mechanical properties of the materials and of tooth components

	Young's Modulus	**Poisson's Ratio**	**Reference**
Enamel	41	0,31	(29)
Dentin	18,6	0,31	(29)
IPS e.max Press	95±5	0,23	(30)
IPS Empress Direct	15,5	0,24	(31)
Cortical Bone	13,7	0,30	(29)
Cancellous Bone	1,37	0,30	(29)

Von Mises stress values were collected in each component of the three models (X, Y, and Z).

5. Results

Stress distribution was calculated for the three models, after application of increased loads of 200N, 500N and 800N, in two different angles of incidence (45-degrees and 11-degrees). The results were captured in images that are characteristic of the finite element analysis. Those images show a colour schematization of the stress distribution, were blue represents the lowest values and red represents the highest values.

In almost every situation, the finite element analysis registers high stresses at the loading point, particularly when a load point was applied, creating hot spots. To overcome this limitation and to achieve more representative images, with a closer colour scheme to the reality, the von Mises stress values were limited from 0 to 50MPa. The result of this decision was clearly observed.

5.1. Load of 200N in the occlusal surface at an 11-degree angle

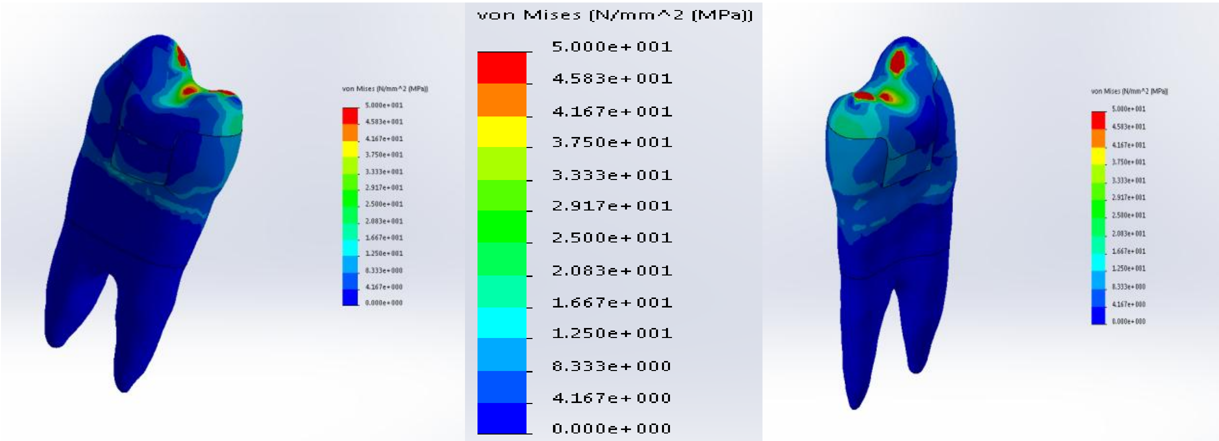

Image 10: a representation of the stress distribution in model A (with the restorative material) after the application of a 200N load in the occlusal surface at an 11-degree angle

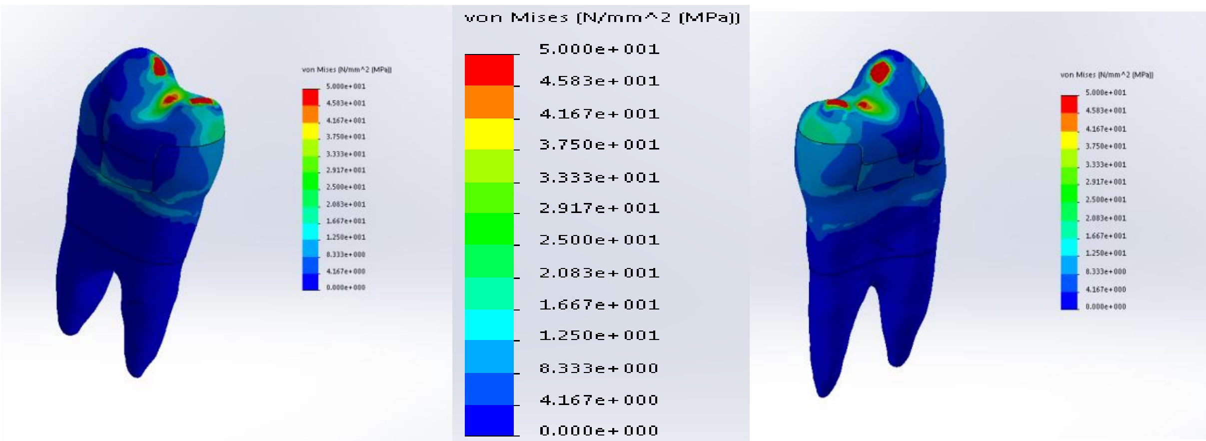

Image 11: a representation of the stress distribution in model B (with the restorative material) after the application of a 200N load in the occlusal surface at an 11-degree angle

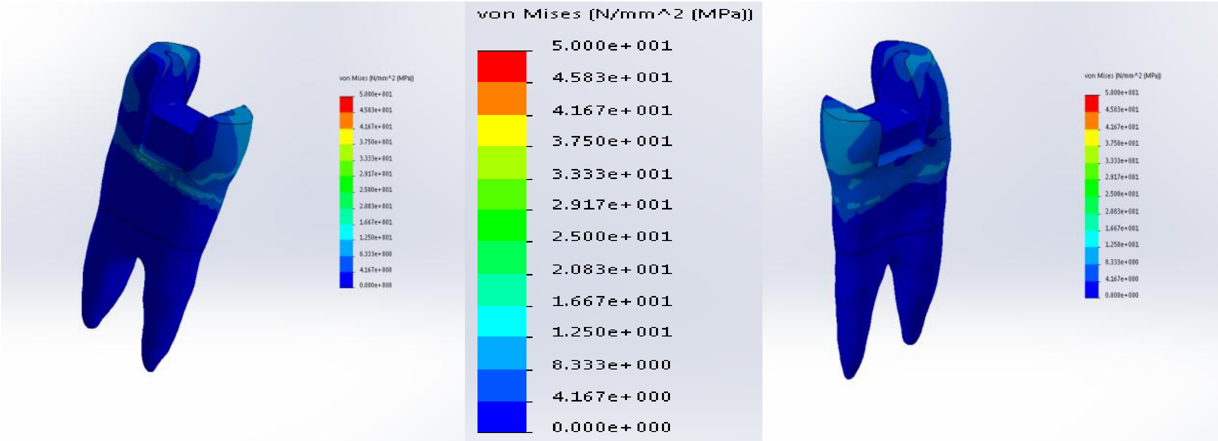

Image 12: a representation of the stress distribution in model A (without the restorative material) after the application of a 200N load in the occlusal surface at an 11-degree angle

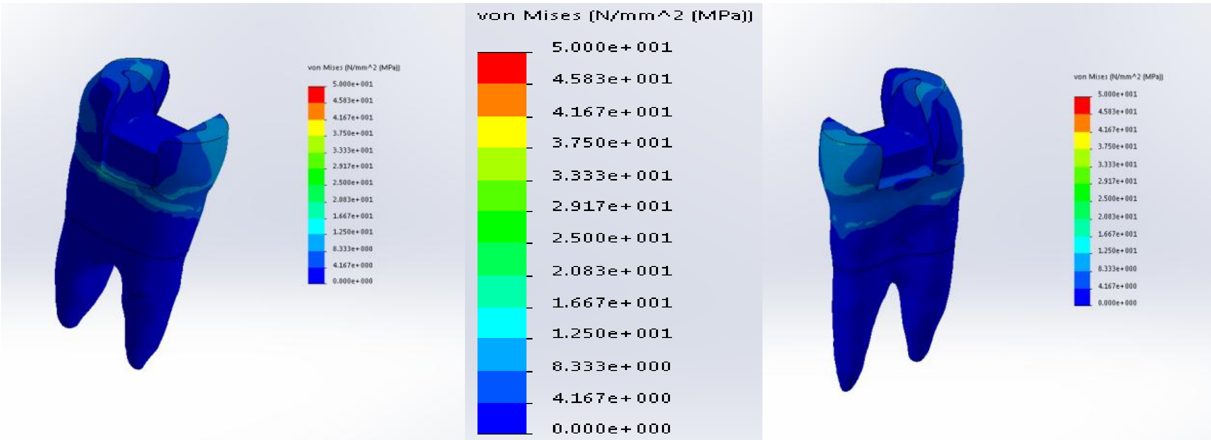

Image 13: a representation of the stress distribution in model B (without the restorative material) after the application of a 200N load in the occlusal surface at an 11-degree angle

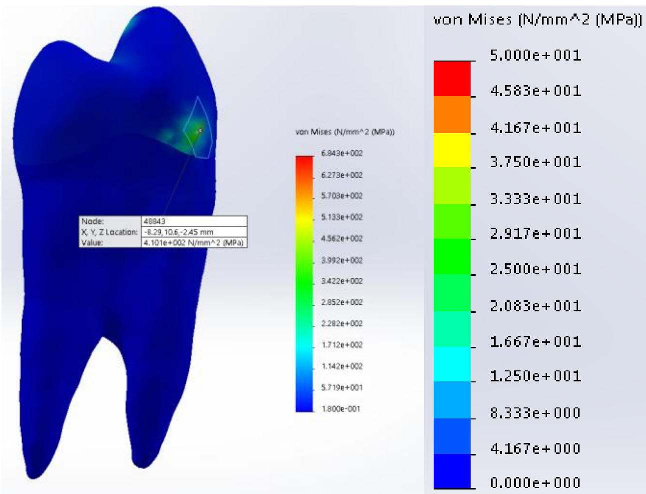

Image 14: a representation of the stress distribution in model C (natural sound tooth) after the application of a 200N load in the occlusal surface at an 11-degree angle

In Image 10 and Image 11, both models show that the highest von Mises stress values registered, after the application of a 200N load in the occlusal surface at an 11-degree angle, are located in the occlusal surface and there is no difference in the stress distribution. It is also possible to see intermediate values in the palatine cusp and some low values in the palatine wall. However, these are almost similar between model A and model B.

When comparing the results shown in the images with model A and model B, both without restorative material (Images 12 and 13), after the application of a 200N load in the occlusal surface at an 11-degree angle, the stress distribution is practically the same.

In model C, after the application of a 200N load in the occlusal surface at an 11-degree angle, the highest von Mises stress values are located in the buccal cervical region (Image 14).

5.2. Load of 500N in the occlusal surface at an 11-degree angle

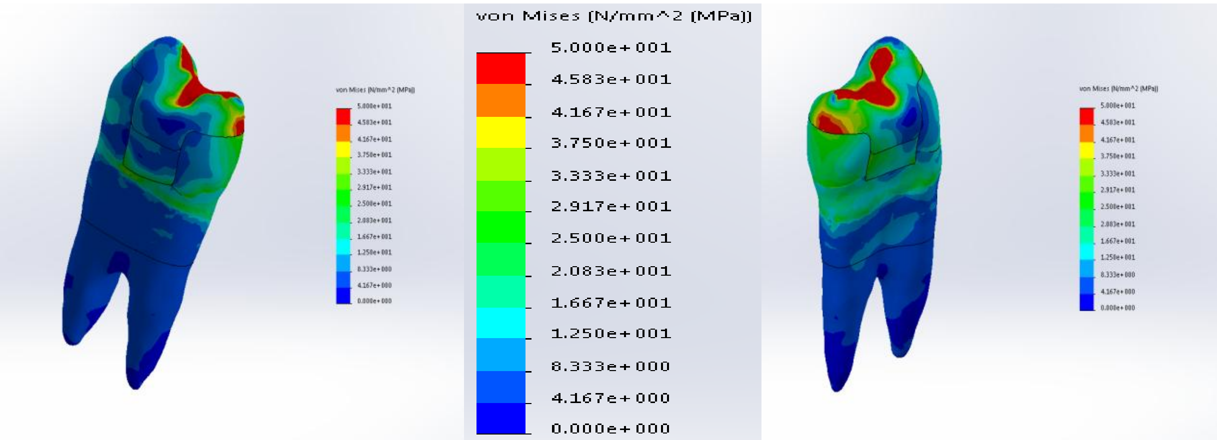

Image 15: a representation of the stress distribution in model A (with the restorative material) after the application of a 500N load in the occlusal surface at an 11-degree angle

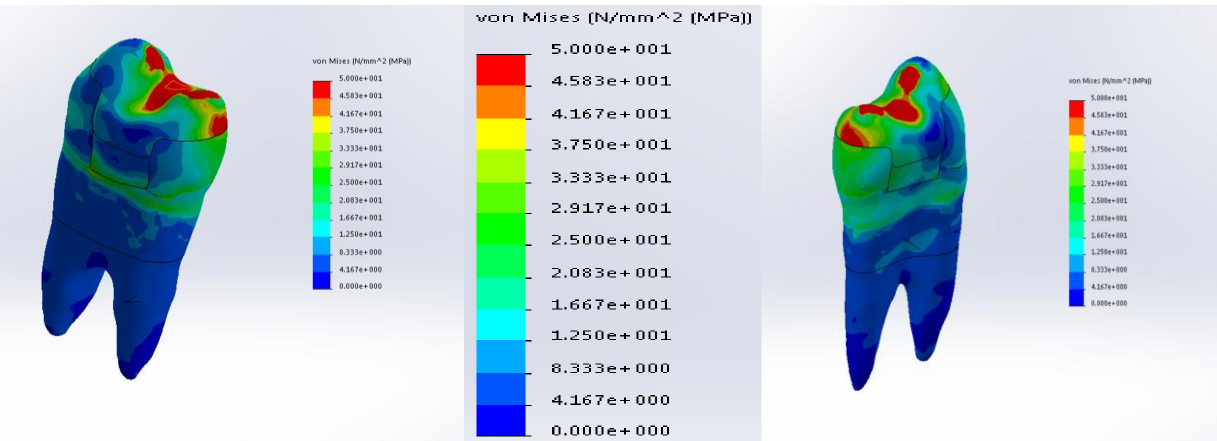

Image 16: a representation of the stress distribution in model B (with the restorative material) after the application of a 500N load in the occlusal surface at an 11-degree angle

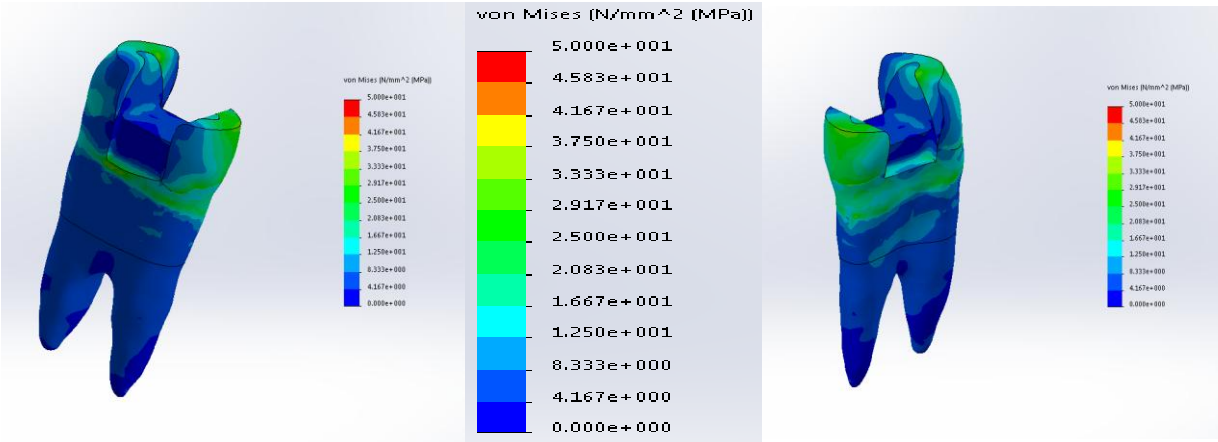

Image 17: a representation of the stress distribution in model A (without the restorative material) after the application of a 500N load in the occlusal surface at an 11-degree angle

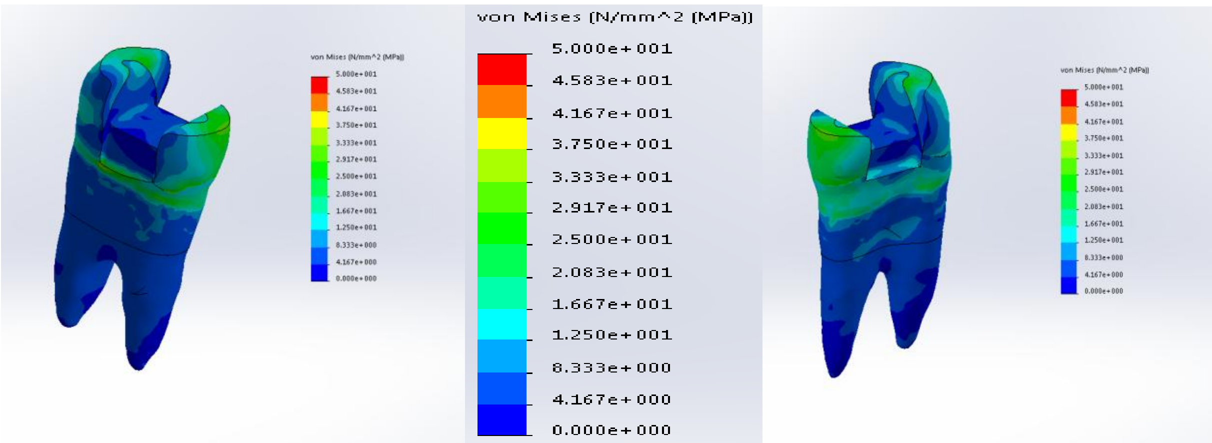

Image 18: a representation of the stress distribution in model B (without the restorative material) after the application of a 500N load in the occlusal surface at an 11-degree angle

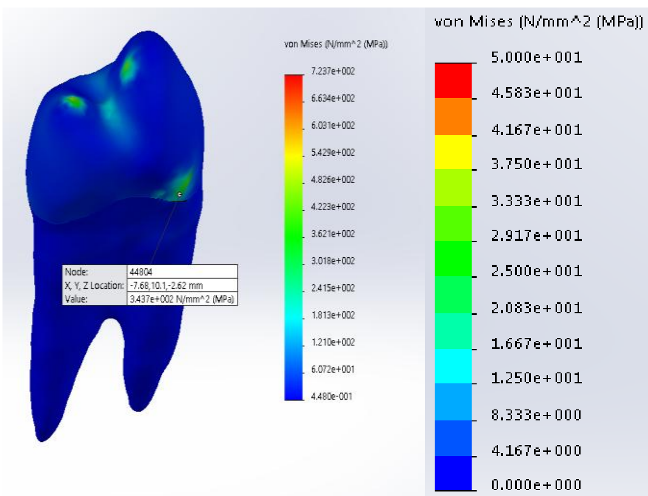

Image 19: a representation of the stress distribution in model C (natural sound tooth) after the application of a 500N load in the occlusal surface at an 11-degree angle

After the application of a 500N load in the occlusal surface at an 11-degree angle, in model A and model B, with the restorative material (Images 15 and 16), the highest von Mises stress values are located in the occlusal surface (load point) and in the palatine cusp. The von Mises stress values in the palatine wall, comparing to the 200N load, are higher. There are some low/medium values in the region below the proximal boxes, around the entire tooth.

When comparing the results shown in the images with model A and model B, both without restorative material (Images 17 and 18), the von Mises stress values are slightly higher in the model B than in model A. However, the difference is not significant. A small area in the upper surface of the vestibular wall can also be seen, where the values of the von Mises stress are at medium ranges.

In model C, after the application of a 500N load in the occlusal surface at an 11-degree angle, the highest von Mises stress values are located in the buccal cervical region (Image 19).

5.3. Load of 800N in the occlusal surface at an 11-degree angle

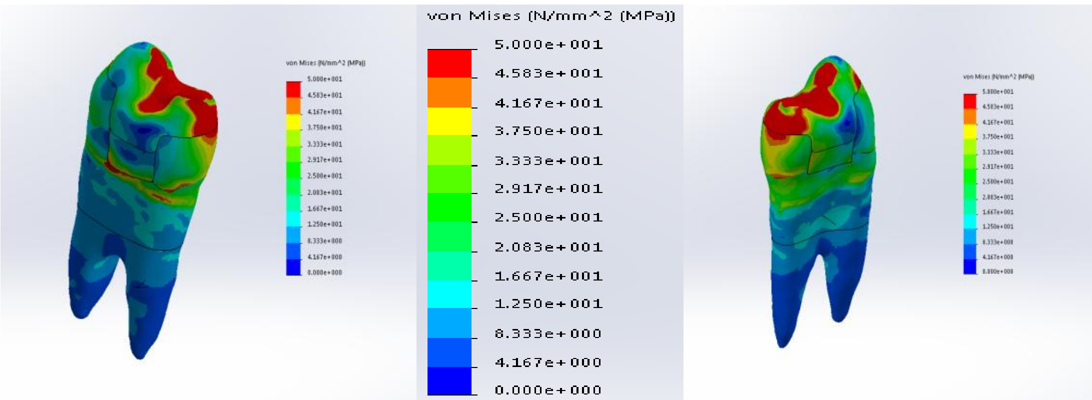

Image 21: a representation of the stress distribution in model B (with the restorative material) after the application of an 800N load in the occlusal surface at an 11-degree

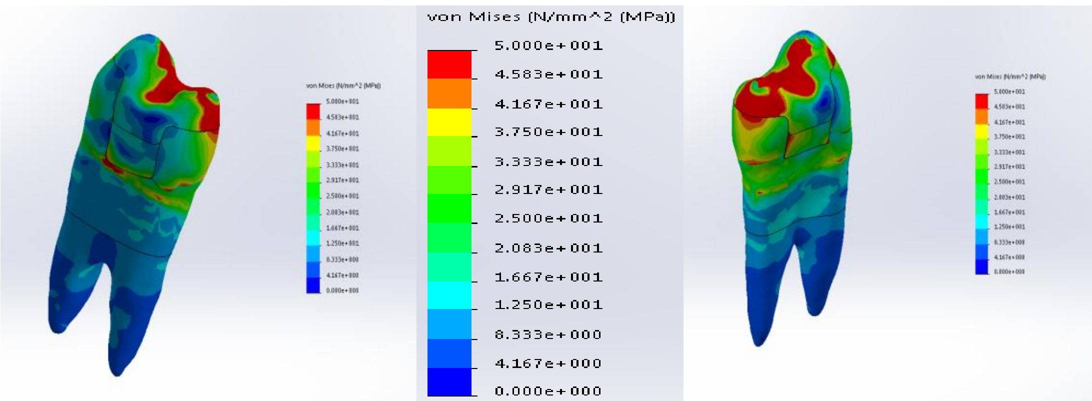

Image 20: a representation of the stress distribution in model A (with the restorative material) after the application of an 800N load in the occlusal surface at an 11-degree

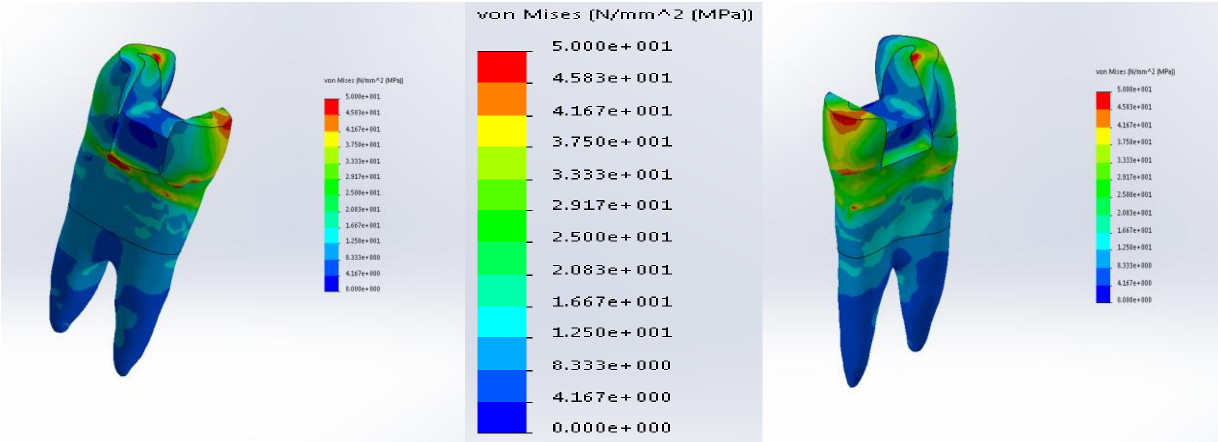

Image 22: a representation of the stress distribution in model A (without the restorative material) after the application of an 800N load in the occlusal surface at an 11-degree angle

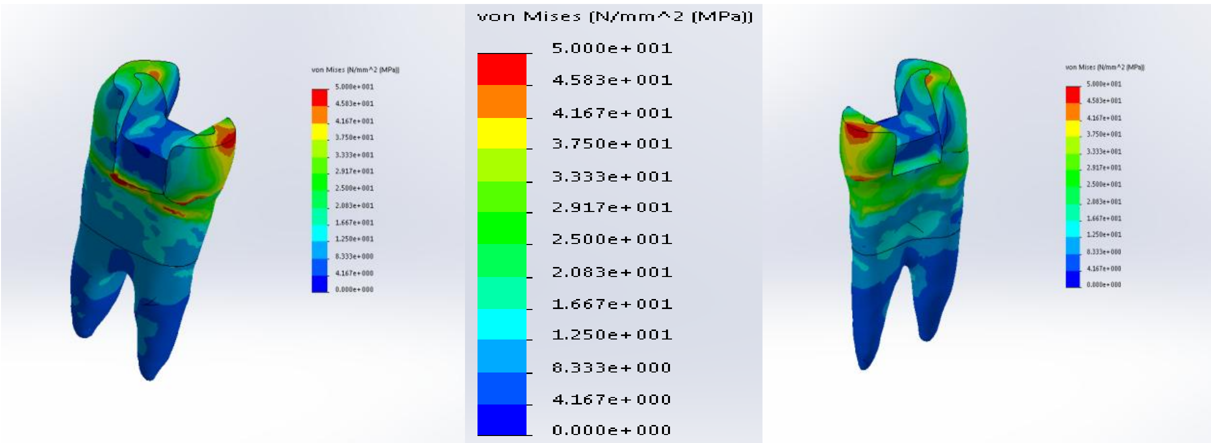

Image 23: a representation of the stress distribution in model B (without the restorative material) after the application of an 800N load in the occlusal surface at an 11-degree angle

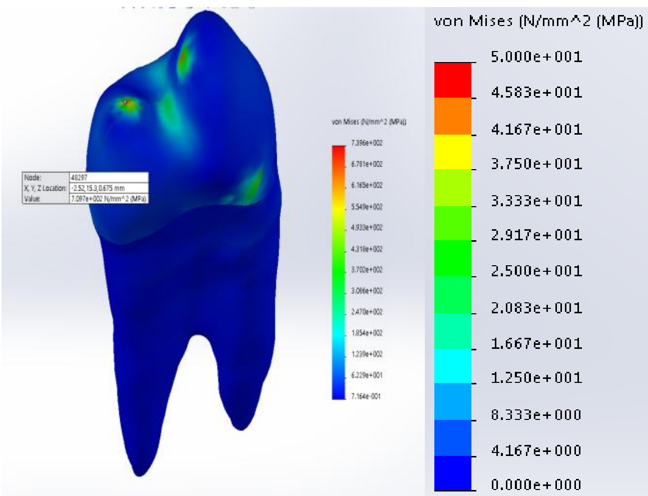

Image 24: a representation of the stress distribution in model C (natural sound tooth) after the application of an 800N load in the occlusal surface at an 11-degree angle

After the application of an 800N load in the occlusal surface at an 11-degree angle, in model A and model B, with the restorative material (Images 20 and 21), the highest von Mises stress values are located in the same place as when the 500N load was applied, but with higher values. Some hot spots are also noticeable in the region near the proximal boxes and in the palatine cervical region, in both models. There is also, in model A, a hot spot in one of the resin filled proximal boxes.

Comparing the stress distribution in model A and model B, both without restorative material (Images 22 and 23), after the application of an 800N load in the occlusal surface at an 11-degree angle, the stress distribution is equal. There is one hot spot in the upper surface of the buccal wall, in both models, but with higher values in model A.

Again, in model C, after the application of a 500N load in the occlusal surface at an 11-degree angle, the highest von Mises stress values are in the buccal cervical region (Image 24).

5.4. Load of 200N in the internal side of the buccal cusp at a 45-degree angle

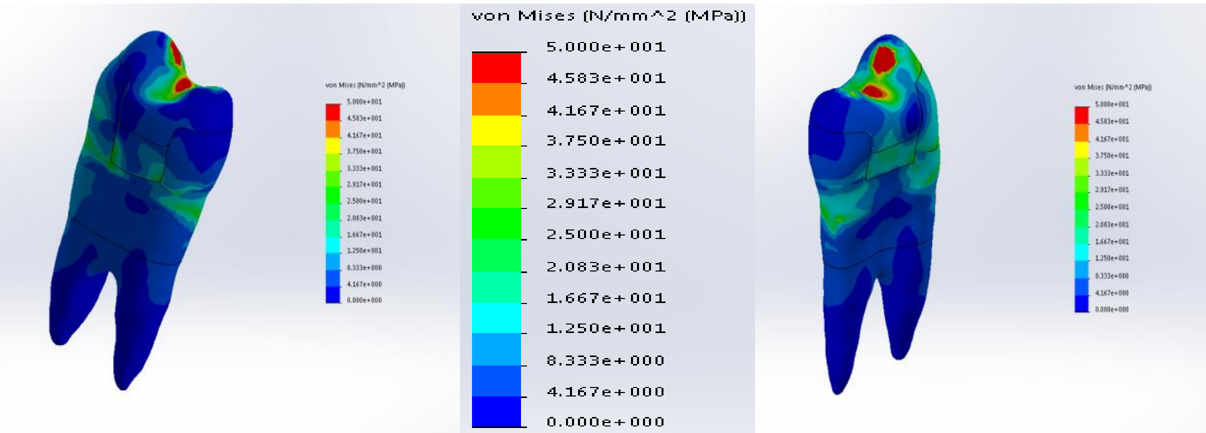

Image 25: a representation of the stress distribution in model A (with the restorative material) after the application of a 200N load in the occlusal surface at a 45-degree angle

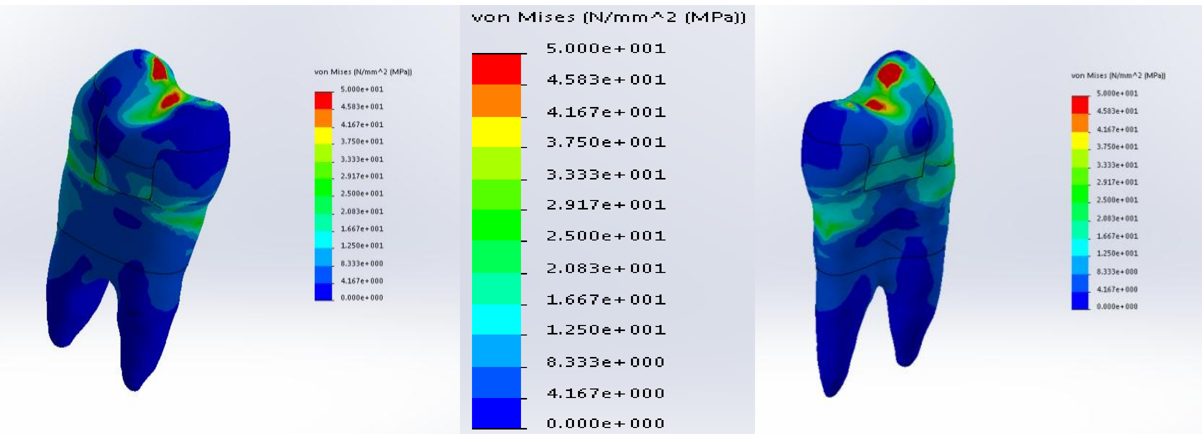

Image 26: a representation of the stress distribution in model B (with the restorative material) after the application of a 200N load in the occlusal surface at a 45-degree angle

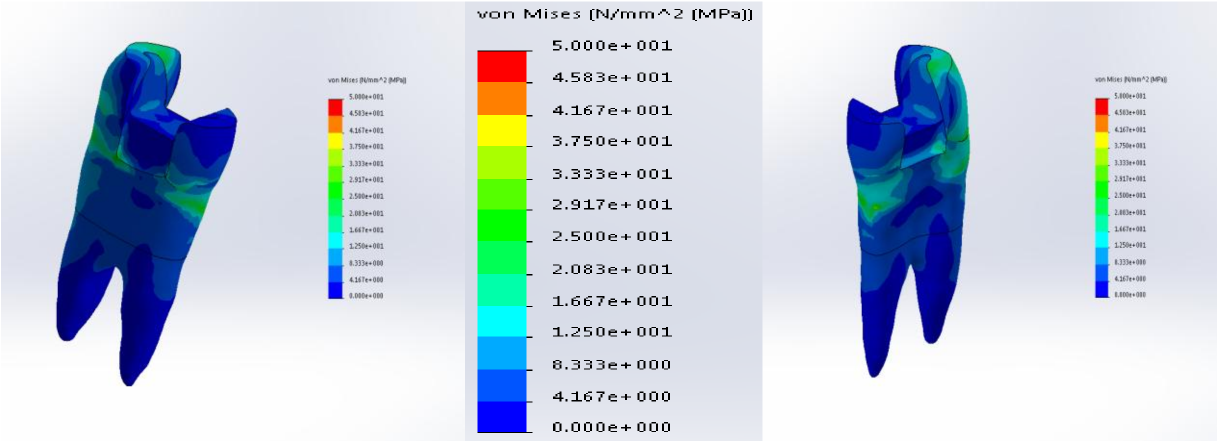

Image 27: a representation of the stress distribution in model A (without the restorative material) after the application of a 200N load in the occlusal surface at a 45-degree angle.

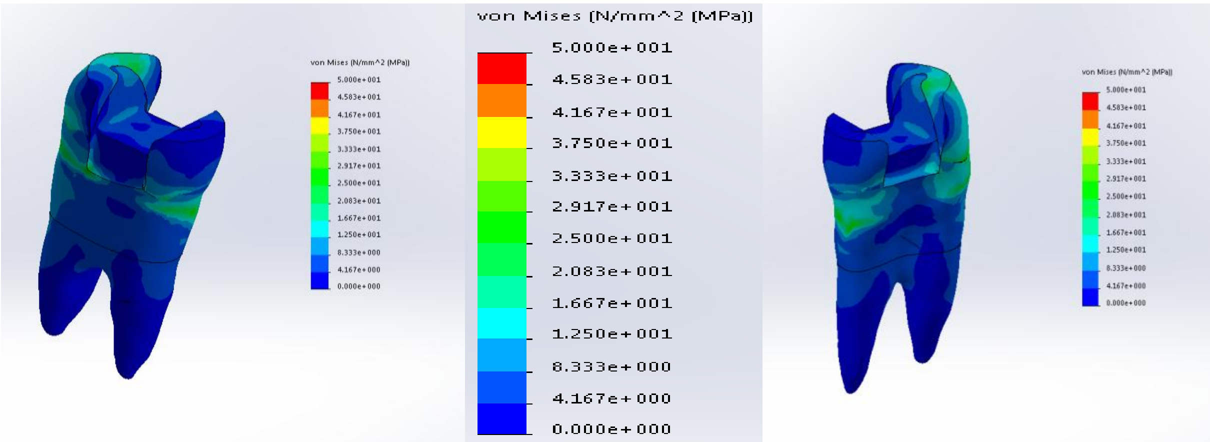

Image 28: a representation of the stress distribution in model B (without the restorative material) after the application of a 200N load in the occlusal surface at a 45-degree angle

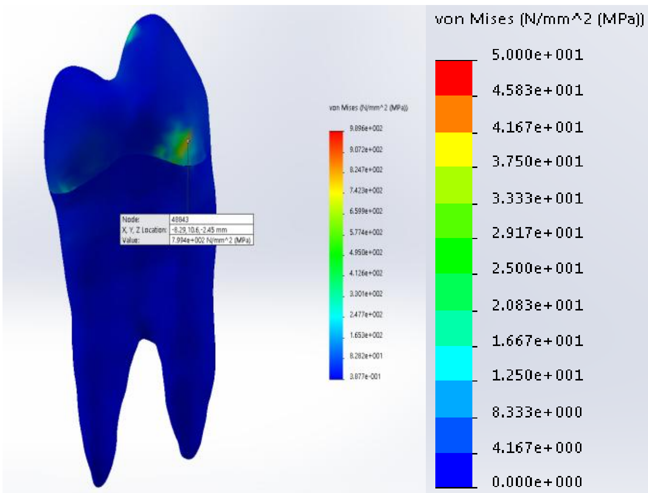

Image 29: a representation of the stress distribution in model C (natural sound tooth) after the application of a 200N load in the occlusal surface at a 45-degree angle

After the application of a 200N load in the occlusal surface at a 45-degree angle, in model A and model B, with the restorative material (Images 25 and 26), the highest values are in the load area. It is possible to observe low/medium values in the area below the proximal boxes around the entire tooth, as well as in the proximal boxes.

In the images with model A and model B, both without restorative material (Images 27 and 28), besides the area below the proximal boxes around the entire tooth, there is an evident stress accumulation in the upper surface of the buccal wall.

In model C, after the application of an 800N load in the occlusal surface at a 45-degree angle, the highest von Mises stress values are located in the buccal cervical region (Image 29).

5.5. Load of 500N in the internal side of the buccal cusp, at a 45-degree angle

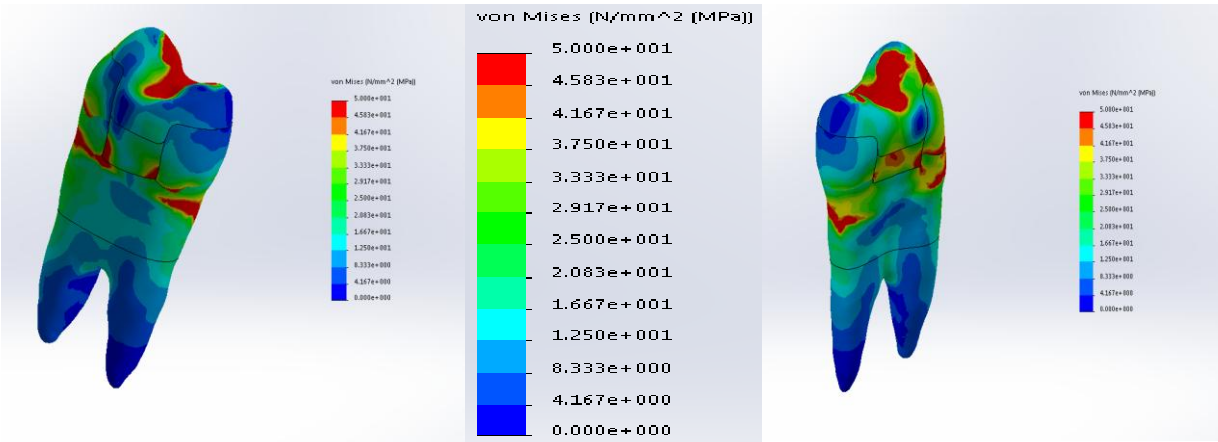

Image 30: a representation of the stress distribution in model A (with the restorative material) after the application of a 500N load in the occlusal surface at a 45-degree angle

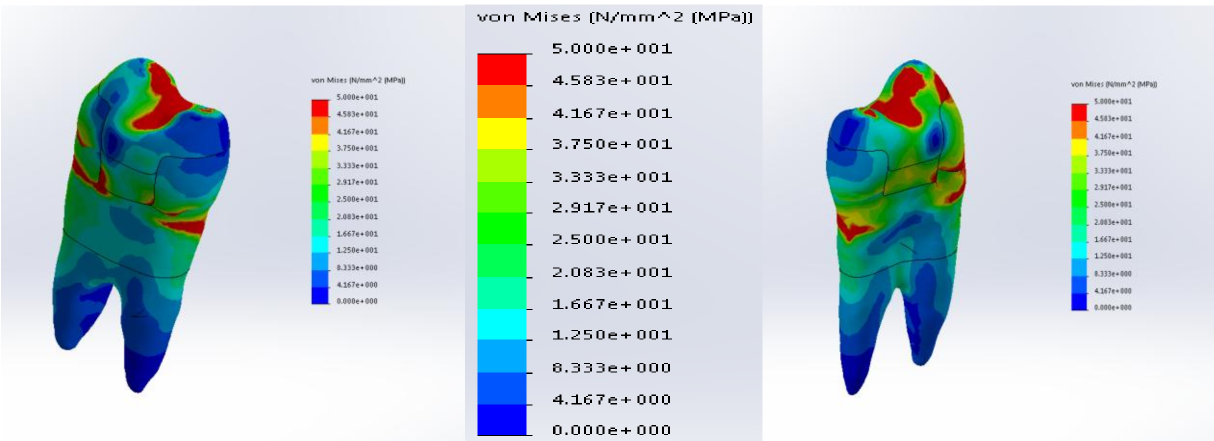

Image 31: a representation of the stress distribution in model B (with the restorative material) after the application of a 500N load in the occlusal surface at a 45-degree angle

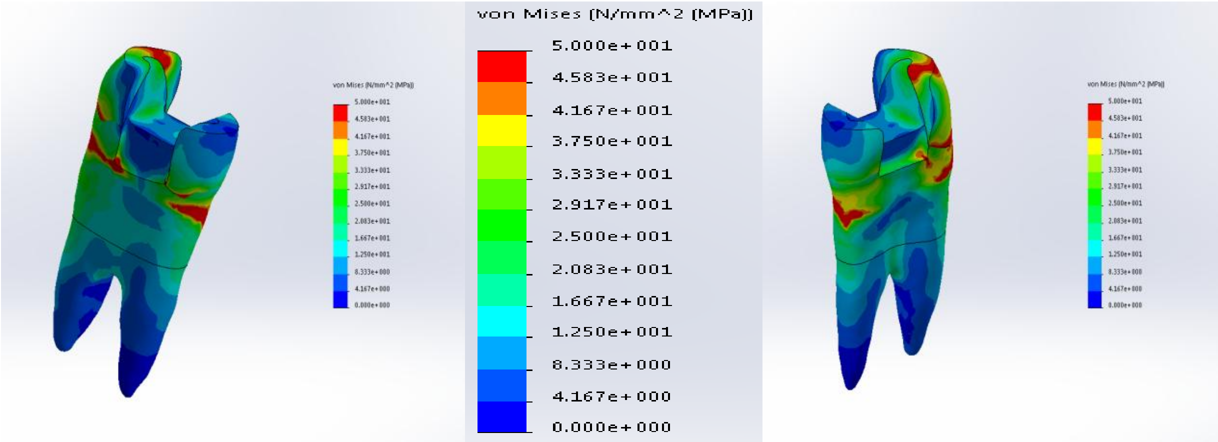

Image 32: a representation of the stress distribution in model A (without the restorative material) after the application of a 500N load in the occlusal surface at a 45-degree angle.

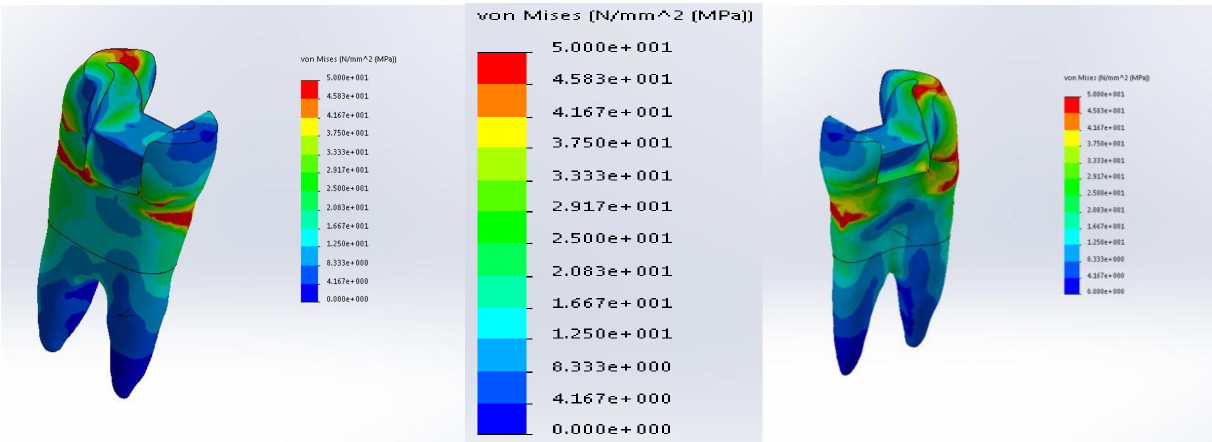

Image 33: a representation of the stress distribution in model B (without the restorative material) after the application of a 500N load in the occlusal surface at a 45-degree angle

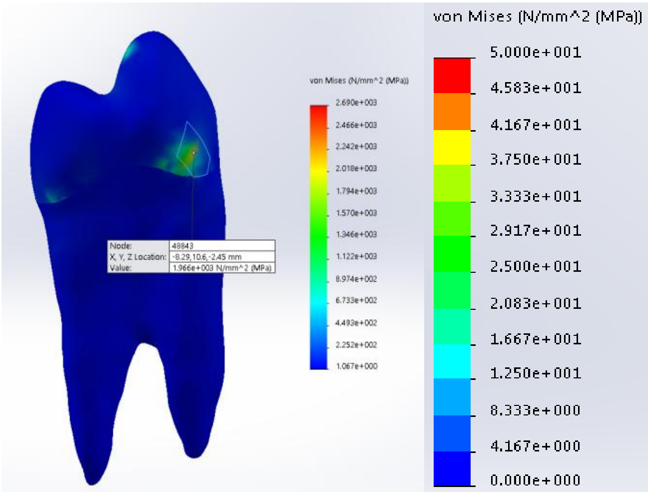

Image 34: a representation of the stress distribution in model C (natural sound tooth) after the application of a 500N load in the occlusal surface at a 45-degree angle

After the application of a 500N load in the occlusal surface at a 45-degree angle, in model A and model B, with the restorative material (Images 30 and 31), the highest values are in the load area, the cervical buccal region, the palatine area below the CEJ and in the angles of the proximal boxes. There is also a high value in model A located in the resin that filled up the subgingival box (deep margin elevation).

In the images with model A and model B, both without restorative material (Images 32 and 33), the stress distribution is equal as in the 200N load at a 45-degree angle. The only difference from model A to model B is that in model A the von Mises stress value in the upper surface is higher and there seems to be a vast stress accumulation in the proximal boxes.

In model C, after the application of an 800N load in the occlusal surface at a 45-degree angle, the highest von Mises stress values are in the buccal cervical region (Image 34).

5.6. Load of 800N in the internal side of the buccal cusp, at a 135-degree angle

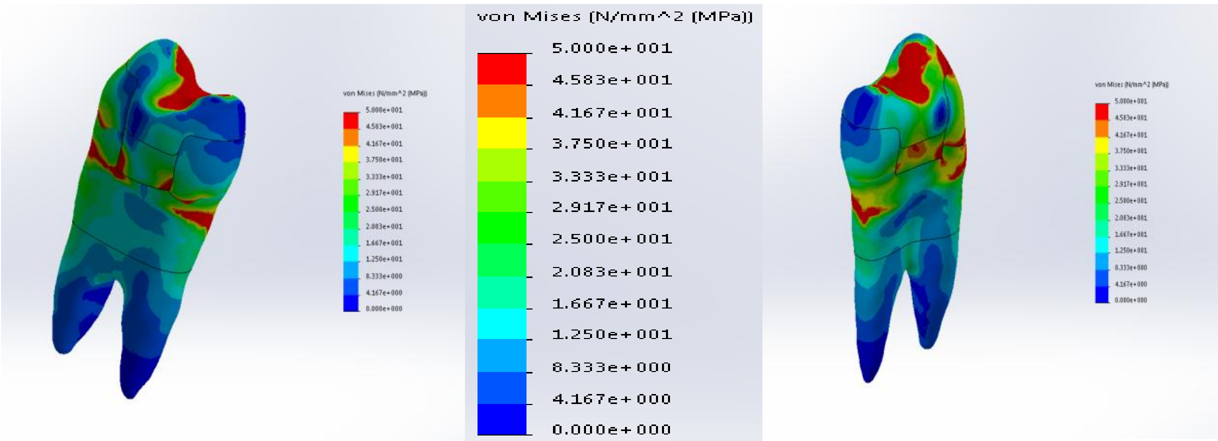

Image 35: a representation of the stress distribution in model A (with the restorative material) after the application of an 800N load in the occlusal surface at a 45-degree angle

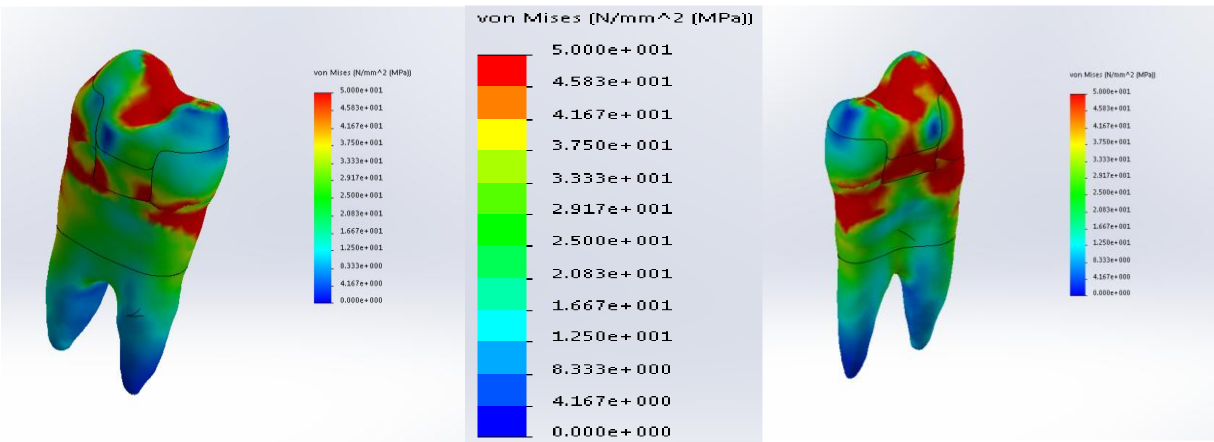

Image 36: a representation of the stress distribution in model B (with the restorative material) after the application of an 800N load in the occlusal surface a 45-degree angle

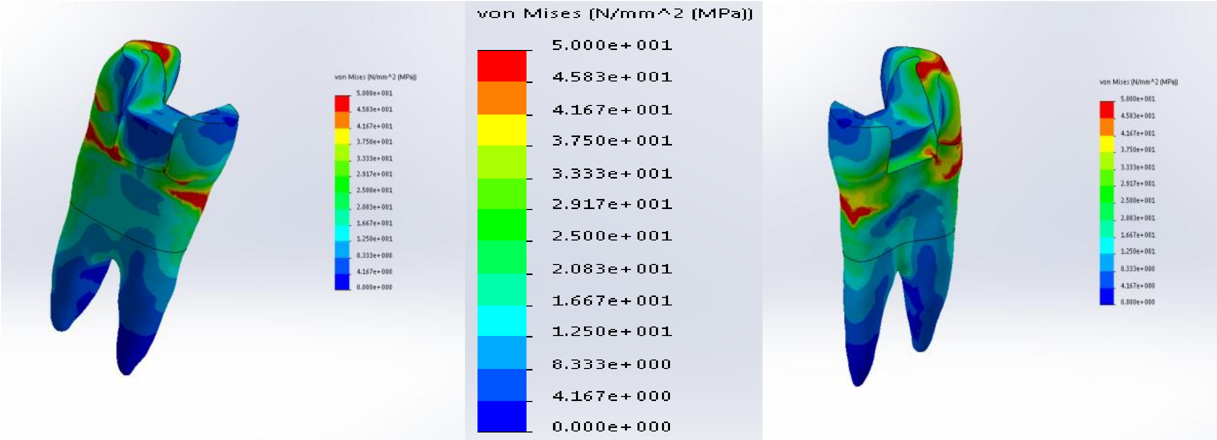

Image 37: a representation of the stress distribution in model A (without the restorative material) after the application of an 800N load in the occlusal surface at a 45-degree angle.

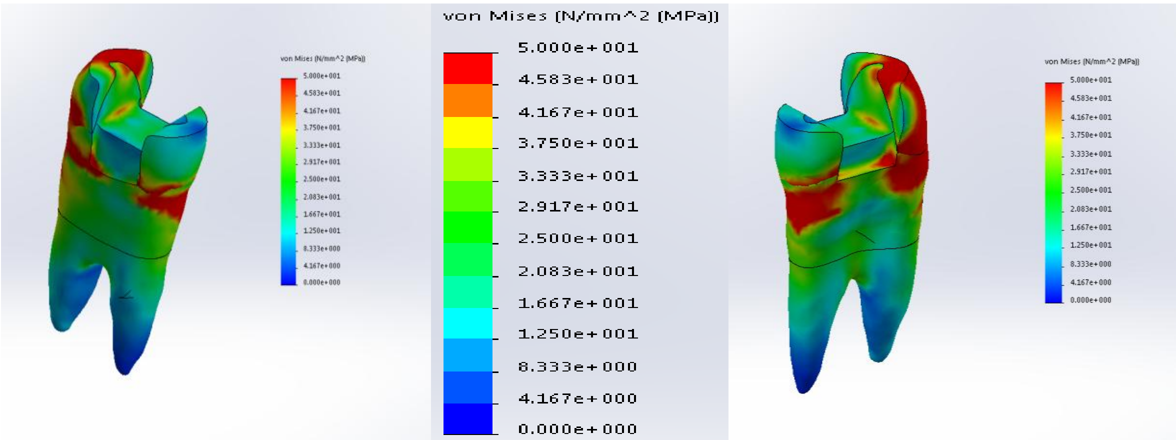

Figure 38: a representation of the stress distribution in model B (without the restorative material) after the application of an 800N load in the occlusal surface at a 45-degree angle

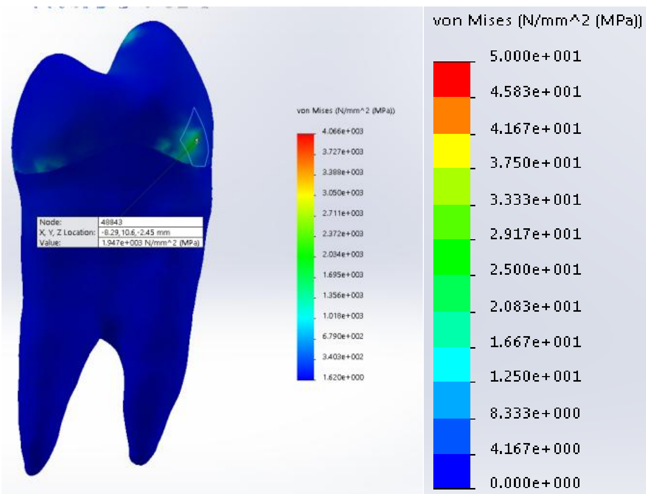

Image 39: a representation of the stress distribution in model C (natural sound tooth) after the application of an 800N load in the occlusal surface at a 45-degree angle

In this finite element analysis results, the stress distribution observed when an 800N load is applied in the internal side of the buccal cusp at a 45-degree angle is the most interesting. As seen in Images 35 and 36, which represent the stress distribution in model A and in model B (with restorative material), the difference between the stress distributions in the two models is quite significant. In model A (Image 35), the higher von Mises stress values are located in the load point, were the sphere contacted with the tooth, in the buccal cervical region, in the palatine region below the CEJ and in the angles of the proximal boxes. There is also evidence of a hot spot in a proximal box filled with resin, corresponding to the deep margin elevation procedure. In model B (Image 36), the tooth restored with a ceramic onlay and without the application of the deep margin elevation technique, the restored tooth showed much more stress accumulation in almost all of its surface, namely in the loading point, in the buccal surface, the proximal boxes, and the cervical region. Even in the root and in the furcation zone the von Mises stress values are significantly higher in model B.

In the images with model A and model B, both without restorative material (Images 37 and 38), the stress accumulation is much more evident in model B than in model A, mainly in the cervical region, in the buccal surface and in the upper surface of the buccal wall. Also in model B, in the internal surface of the buccal wall, there are some medium/high von Mises stress values, with a hot spot in the angle between the buccal wall and the occlusal floor of the cavity.

In model C, after the application of an 800N load in the occlusal surface at a 45-degree angle, equal to all the other results verified in the control group with other load values and/or with other angle incidence of the load, the highest von Mises stress values are in the buccal cervical region (Image 39).

6. Discussion

Finite element analysis results allow a better knowledge in comprehending the actual process which conducts to failure, while in vitro studies reveal the maximum load to failure for the system being tested(28). Values from Finite Element Analysis are divided as von Mises stress, maximum principle stress (tensile stress), minimum principle stress (compressive stress) and shear stress. Moeen et al states that when brittle materials are used in the studies, such as bone, ceramics or cements, the maximum principle stress would better show the magnitude of stress concentrations and the distributions as this allows to distinguish between tensile and compressive stresses by positive and negative signs, respectively(28). Other aspect that this author refers is that von Mises stress commonly deals with ductile materials, like aluminium or steel, having equal compressive and tensile strength(28). However, in the majority of finite element studies presented in the literature, von Mises stress is used as analysis criteria and there is also evidence that the selection of the von Mises criteria (tensile type normal criteria) seems to be reliable because brittle materials, which the tooth is a member of, fail primarily because of tensile type of stress(26). Therefore, because of these last two details, it was decided to use the von Mises stress, once it is the type of stress most used and referred in the literature. In the future, one of the hypotheses will be to use both or use all the types of stress.

No studies exist that apply the finite element analysis to the the deep margin elevation technique in ceramic onlay restorations, or other type of indirect restorations with ceramics, making this an embryonic study. Even studies or articles that address the deep margin elevation technique are scarce in the literature.

Zaruba et al studied the influence of deep margin elevation technique application on the margins of ceramic inlays by applying a thermomechanical loading to 40 molars prepared with standardized mesial-occlusal-distal class II cavities and restored with ceramic inlays after the subgingival boxes being filled up with composite. They concluded that ceramic inlays restorations after the deep margin elevation technique application result in marginal integrities practically equal to margins of ceramic inlays placed in dentin(22).

Roggendorf et al also studied the influence of the deep margin elevation technique application on composite inlays in vitro. Although this study mentions resin composite restorations and not ceramic ones, they concluded that, with the right type of resin to use in the deep margin elevation technique, there is no difference between the tooth restored with the application of the deep margin elevation technique and the tooth restored without the application of this technique(24).

Ilgenstein et al addressed the influence of the deep margin elevation technique on the marginal integrity and fracture behaviour of root-filled molars restored with CAD/CAM ceramic or composite onlays. In this study, 48 mandibular teeth were divided in 4 groups: G1- with proximal box elevation and restored with feldspathic ceramic onlays; G2- with proximal box elevation and restored with composite onlay; G3- without proximal box elevation and restored with feldspathic ceramic onlays and G4- with proximal box elevation and restored with composite onlay. All specimens were subjected to thermomechanical loading and load-to-fracture test. This study concluded that the deep margin elevation does not influence negatively the marginal integrity or fracture behaviour of root canal-treated tooth restored with ceramic onlays.

Although these studies are not about the stress distribution in teeth restored with ceramic onlays after the application of the deep margin elevation technique, they refer to something exceedingly important about deep margin elevation: the marginal integrity. When filling up subgingival margins with resin composite without rubber dam isolation is considered, the thought that automatically comes to mind is margin deterioration and microleakage. However, the studies mentioned above show that the use of deep margin elevation does not influence the marginal integrity. Of course that the thermomechanical loading used in this study is just a simulation of the oral environment and not the oral environment itself, but these results have feasibility. They make us believe that one of the possible disadvantages of the deep margin elevation technique does not have the impact that is thought to have. Other thing that seems to be very important is the type of resin composite used when applying the deep margin elevation technique. Literature refers two options: highly filled composite or flowable composites(17, 22). Flowable composites seems to be a bad option, because they have higher polymerization shrinkage and may not be sufficiently resistant to deformation under load (inferior mechanical strength), regardless of the simpler application technique(17, 22). Therefore, the best option is to use a highly filled hybrid composite, because they have better mechanical properties(17). The difficulty to adapt the highly filled hybrid composite to cavity walls in a thin layer, because of its viscosity, can be surpassed by pre-heating this type of composite. To approximate our study to the best reality possible, we used an IPS Empress Direct, from Ivoclar Vivadent, that is a highly filled nanohybrid resin composite.

Analysing the stress distribution that we obtained in our study, the first thing that we can observe is that the loads applied with a 45-degree angle incidence cause more stress accumulation that the force applied with a 11-degree angle incidence. This happens because the eccentric forces (45-degree angle incidence) are much more destructive than the concentric forces (11-degree angle incidence). In all the loads applied with the 11-degree angle incidence, the von Mises stress values seem to be slightly higher in the tooth restored with a proximal box elevation where the deep proximal boxes were filled up with composite resin and an all-ceramic onlays (model A), when compared to the tooth restored without the execution of the proximal box elevation technique and with an all-ceramic onlay (model B). However, the difference is not significant. In the 200N and 500N loads with a 45-angle degree, the stress distribution is practically the same in both models, but the von Mises stress values are higher than the values registered with the 11-degree angle incidence, like was said before. However, in the 800N load with a 11-degree angle incidence, the stress distribution of model A and model B was quite different. Model B presents much more stress accumulation than model A, when it is applied an 800N load with a 45-degree angle incidence in the internal side of the buccal cusp. This could be an evidence that the resin used to fill up the subgingival proximal boxes in model A (deep margin elevation technique) behaves like a stress absorber or stress breaker during loading(22). An explication to this might be the fact that composite resins have mechanical properties similar to dentin and this may possibly result in the reduction of the stress generated on residual hard tissue(23). In the stress distribution after the application of a 800N load with a 45-degree angle, we can also see some medium/high von Mises stress values, with a hot spot in the angle between the buccal wall and the occlusal floor of the cavity. This could be a sign of a possible catastrophic fracture. The literature affirms that ceramic restorations have a higher probability of catastrophic fractures, because they have high elastic modulus and this leads to fewer loads being absorbed within the ceramic when compared to composite resin(9, 12). As the ceramic disseminates more of the applied load to the subjacent tooth structure, it favoured the occurrence of more severe fractures(9).

In model C, in all the loads applied with the two incidences, the highest values were all verified in the buccal cervical region, in the enamel adjacent to the cementoenamel junction. This happens because the enamel in this area is thinner than the other areas, as the enamel rod arrangement has an orientation slightly more to the root, in contrary to the other regions of the crown were the enamel rods have a perpendicular orientation to the subjacent enamel-dentine junction, and the fragile bond between the enamel and dentin in the cervical region may also contribute to the occurrence of high stress accumulation in the enamel(32).

This study had some limitations. The first one was the software chosen, SolidWorks. This program is a basic program to do 3D reconstruction and modelling of objects and finite element analysis. It's good to teach students or people starting to work in this area, but to be used in complex studies like this one, it's not the most indicated due of the limitations of the own program. The principal limitation that we observed was the non-convergence of some nodes in the transition from one type of material to another. This is more evident when zooming the transitions, as mesh imperfections resulted from the presence of some little gaps. Another problem faced in the study using SolidWorks software was the impossibility of creating a one piece all-ceramic onlay in model B. The solution found by the engineering students and the investigators of this scientific work was to fill up the subgingival proximal boxes with the ceramic material and then place the ceramic onlay on top. This was the solution found to overcome the problem and to simulate a one piece all-ceramic onlay in model B.

The results obtained with finite element analysis can be validated comparing them with the relevant data available in literature. After our research, as said previously, it is possible to clearly state that there is no data available in the literature about finite element analysis and the application of the deep margin elevation technique in ceramic onlay restorations, so we cannot validate our study. However, the finite element analysis of this subject matter, even with the limitations that were referred, seems to be very interesting, what makes this pioneering study a starting point to something greater. Therefore, the next step will be to plan and perform a non-linear finite element analysis in more advanced and capable software, like Nastran/Patran (MSC Software Corporation) or ADINA (Adina R & D, Inc.), for example. Although the non-linear finite element analysis is more complex and requires more monitoring and more computational requirements and time, it allows the inclusion of hyperelasic structures, like the periodontal ligament and the pulp. This will allow a more realistic simulation and more reliable results, since these structures will have some influence in the stress distribution, namely the periodontal ligament. Literature sustains that the non-linear simulation of periodontal properties gives precision and reliability to the calculated stress and strain with a wide range of tooth movements(26). The use of a more advanced and capable program will allow the definition of the cementum and the adhesive interface, which, once more, will further approximate the study to reality. The final step to validate the results obtained would be to conduct an in vitro experiment on the same study matter(28).

7. Conclusion

Regardless the stated limitations, according to the results of the study, it was concluded that, from a biomechanical point of view, ceramic onlay restorations of teeth with subgingival margins using the deep margin elevation technique, seem to be advantageous. This benefit appears to be more evident when the load applied is very high (800N in this case) and when it comes to eccentric forces (more destructive). Regarding the stress distribution obtained with 200N, 500N and 800N loads with an 11-degree angle incidence and with the application of 200N and 500N loads with an 45-degree angle incidence, there was no significant difference between the model where the deep margin elevation technique was used and the model where that technique was not.

8. Acknowledgement

First, I want to thank my family, especially my father, my mother, my brother, my grandmother and my grandfather, for in these years of faculty, as they did along all my life, they have always been by my side, giving me all the strength of the world in bad times and sharing with joy and pride the good times. And, of course, thanks to my girlfriend for all the comprehension, support and affection that she gives me.

To all my teachers, a very sincere thank you for doing everything for me to become the best professional possible. And an even bigger thanks to the teachers who, besides having done everything for me to become the best professional possible, made me a better person too.

To all my friends, thank you for the friendship and for the support that they have given me over these years. A special thanks to my teammates for having been my second family and thanks for having been a constant source of happiness and friendship all these years.

Thanks to Engineer Estevam de Las Casas for helping us at the beginning of the project, kindly providing us the 3D model. Thanks to Engineer and Professor Luís Roseiro from ISEC and to his students Rui Cararrinho, André Oliveira and Júlio Regado for having been fundamental in the 3D modeling and for having been such a great help and support, always ready to explain what we did not understand. And many thanks to Doctor Jon Gurrea for having collaborated with us on this project, it was truly an honor.

Finally, thanks to my supervisor, Professor Fernando Guerra, and to my co-supervisor, Professor Rui Isidro Falacho for having been part of my academic path, for having accepted me in such an interesting project that gave me so much pleasure and pride to do, as well as for always being available to help, advise and correct, at all times with the objective of making this project reach success.

9. Bibliographic References

1. Kois DE, Chaiyabutr Y, Kois JC. Comparison of load-fatigue performance of posterior ceramic onlay restorations under different preparation designs. Compendium of continuing education in dentistry. 2012;33 Spec No 2:2-9.
2. Biacchi GR, Tofano G, Filho AT, Kina S. RestauraçÕes estéticas cerâmicas e endocrowns na reabilitação de dentes posteriores. Esthetic ceramic restorations and endocrowns in rehabilitation of posterior teeth. 2012;9(4):98-105.
3. Naeselius K, Arnelund CF, Molin MK. Clinical evaluation of all-ceramic onlays: a 4-year retrospective study. The International journal of prosthodontics. 2008;21(1):40-4.
4. Cubas GBdA, Habekost L, Camacho GB, Pereira-Cenci T. Fracture resistance of premolars restored with inlay and onlay ceramic restorations and luted with two different agents. Journal of Prosthodontic Research. 2011;55(1):53-9.
5. Thompson MC, Thompson KM, Swain M. The all-ceramic, inlay supported fixed partial denture. Part 1. Ceramic inlay preparation design: a literature review. Australian dental journal. 2010;55(2):120-7; quiz 231.
6. Busato PdMR, Simon GHP, Camilotti V, Nasar PO, Vendrame T, Moura SK. Aspectos clínicos da técnica de preparo e restauração onlay de porcelana em dentes posteriores. Clinical aspects of the technique for porcelain onlay preparation and restoration in posterior teeth. 2010;7(4):60-7.
7. Aguiar TR, Lima AF, Voltarelli FR, Martins LRM. Associação de técnicas no tratarnento restaurador em dentes posteriores: onlay cerâmico x resina corn posta. Revista Dental Press de Estética. 2010;7(1):82-93.
8. Guess PC, Vagkopoulou T, Zhang Y, Wolkewitz M, Strub JR. Marginal and internal fit of heat pressed versus CAD/CAM fabricated all-ceramic onlays after exposure to thermo-mechanical fatigue. Journal of dentistry. 2014;42(2):199-209.
9. Bianchi ESAA, Ghiggi PC, Mota EG, Borges GA, Burnett LH, Jr., Spohr AM. Influence of restorative techniques on fracture load of endodontically treated premolars. Stomatologija / issued by public institution "Odontologijos studija" [et al]. 2013;15(4):123-8.
10. Guess PC, Schultheis S, Wolkewitz M, Zhang Y, Strub JR. Influence of preparation design and ceramic thicknesses on fracture resistance and failure modes of premolar partial coverage restorations. The Journal of prosthetic dentistry. 2013;110(4):264-73.
11. Soares CJ, Martins LR, Fonseca RB, Correr-Sobrinho L, Fernandes Neto AJ. Influence of cavity preparation design on fracture resistance of posterior Leucite-reinforced ceramic restorations. The Journal of prosthetic dentistry. 2006;95(6):421-9.

12. Morimoto S, Vieira GF, Agra CM, Sesma N, Gil C. Fracture strength of teeth restored with ceramic inlays and overlays. Brazilian dental journal. 2009;20(2):143-8.

13. Ozyoney G, Yan Koglu F, Tagtekin D, Hayran O. The efficacy of glass-ceramic onlays in the restoration of morphologically compromised and endodontically treated molars. The International journal of prosthodontics. 2013;26(3):230-4.

14. Habekost Lde V, Camacho GB, Pinto MB, Demarco FF. Fracture resistance of premolars restored with partial ceramic restorations and submitted to two different loading stresses. Operative dentistry. 2006;31(2):204-11.

15. Bitter K, Meyer-Lueckel H, Fotiadis N, Blunck U, Neumann K, Kielbassa AM, et al. Influence of endodontic treatment, post insertion, and ceramic restoration on the fracture resistance of maxillary premolars. International endodontic journal. 2010;43(6):469-77.

16. Boushell LW, Ritter AV. Ceramic inlays: a case presentation and lessons learned from the literature. Journal of esthetic and restorative dentistry : official publication of the American Academy of Esthetic Dentistry [et al]. 2009;21(2):77-87.

17. Rocca GT, Rizcalla N, Krejci I, Dietschi D. Evidence-based concepts and procedures for bonded inlays and onlays. Part II. Guidelines for cavity preparation and restoration fabrication. The international journal of esthetic dentistry. 2015;10(3):392-413.

18. Pol CW, Kalk W. A systematic review of ceramic inlays in posterior teeth: an update. The International journal of prosthodontics. 2011;24(6):566-75.

19. Ona M, Watanabe C, Igarashi Y, Wakabayashi N. Influence of preparation design on failure risks of ceramic inlays: a finite element analysis. The journal of adhesive dentistry. 2011;13(4):367-73.

20. Shibata S, Gondo R, Araujo E, Mello Roesler CR, Baratieri LN. Influence of surrounding wall thickness on the fatigue resistance of molars restored with ceramic inlay. Brazilian oral research. 2014;28.

21. Krifka S, Anthofer T, Fritzsch M, Hiller KA, Schmalz G, Federlin M. Ceramic inlays and partial ceramic crowns: influence of remaining cusp wall thickness on the marginal integrity and enamel crack formation in vitro. Operative dentistry. 2009;34(1):32-42.

22. Zaruba M, Gohring TN, Wegehaupt FJ, Attin T. Influence of a proximal margin elevation technique on marginal adaptation of ceramic inlays. Acta odontologica Scandinavica. 2013;71(2):317-24.

23. Ilgenstein I, Zitzmann N, Bühler J, Wegehaupt F, Attin T, Weiger R, et al. Influence of proximal box elevation on the marginal quality and fracture behavior of root-filled molars restored with CAD/CAM ceramic or composite onlays. Clinical oral investigations. 2015;19(5):1021-8.

24. Roggendorf MJ, Kramer N, Dippold C, Vosen VE, Naumann M, Jablonski-Momeni A, et al. Effect of proximal box elevation with resin composite on marginal quality of resin composite inlays in vitro. Journal of dentistry. 2012;40(12):1068-73.

25. Magne P, Spreafico RC. Deep Margin Elevation: A Paradigm Shift. American Journal of Esthetic Dentistry. 2012;2(2):86-96.

26. Srirekha A, Bashetty K. Infinite to finite: an overview of finite element analysis. Indian journal of dental research : official publication of Indian Society for Dental Research. 2010;21(3):425-32.

27. Hammond D, Whitty J. Finite element analysis and dentistry. Faculty Dental Journal. 2015;6(3):134-9.

28. Moeen F, Nisar S, Dar N. A STEP BY STEP GUIDE TO FINITE ELEMENT ANALYSIS IN DENTAL IMPLANTOLOGY. Pakistan Oral & Dental Journal. 2014;34(1):164-9.

29. Yikilgan I, Bala O. How can stress be controlled in endodontically treated teeth? A 3D finite element analysis. TheScientificWorldJournal. 2013;2013:426134.

30. Vivadent I. IPS e.max Press Scientific Documentation. In: Vivadent I, editor. Ivoclar Vivadent Scientific Documentation2011.

31. Vivadent I. IPS Empress Direct Scientific Documentation. In: Vivadent I, editor. Ivoclar Vivadent Scientific Documentation2010.

32. Kartik R, Sesha R, Bheemalingeswar R, Durga K, Satheesh M. Cervical stress due to normal occlusal loads is a cause for abfraction? – A finite element model study. Journal of Orofacial Sciences. 2012;4(2):120-3.