

Effect of Ceramic Thickness and Composite Bases on Stress Distribution of Inlays - A Finite Element Analysis

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The purpose of this study was to determine the effect of cavity depth, ceramic thickness, and resin bases with different elastic modulus on von Mises stress patterns of ceramic inlays. Tridimensional geometric models were developed with SolidWorks image software. The differences between the models were: depth of pulpal wall, ceramic thickness, and presence of composite bases with different thickness and elastic modulus. The geometric models were constrained at the proximal surfaces and base of maxillary bone. A load of 100 N was applied. The stress distribution pattern was analyzed with von Mises stress diagrams. The maximum von Mises stress values ranged from 176 MPa to 263 MPa and varied among the 3D-models. The highest von Mises stress value was found on models with 1-mm-thick composite resin base and 1-mm-thick ceramic inlay. Intermediate values (249-250 MPa) occurred on models with 2-mm-thick composite resin base and 1-mm-thick ceramic inlay and 1-mm-thick composite resin base and 2-mm-thick ceramic inlay. The lowest values were observed on models restored exclusively with ceramic inlay (176 MPa to 182 MPa). It was found that thicker inlays distribute stress more favorably and bases with low elastic modulus increase stress concentrations on the internal surface of the ceramic inlay. The increase of ceramic thickness tends to present more favorable stress distribution, especially when bonded directly onto the cavity without the use of supporting materials. When the use of a composite base is required, composite resin with high elastic modulus and reduced thickness should be preferred.

Key Words: inlays, composite resins, computational simulation, finite element analysis, dental porcelain.

Introduction

Biomechanical behavior similar to natural teeth is expected when porcelain and composite resins are used together to replace lost enamel and dentin (1). One way to combine these materials is by applying the composite basing technique, in which composite resins replace lost dentin and serve as a supporting structure for the ceramic that replaces the missing enamel.

Composite bases under restorations are used for filling up internal undercuts, to even out cavity floor and reduce volume of restorations (2). Despite the widespread use of composite bases, there are few studies that assess their influence on strength of the tooth/restoration complex and how this procedure can affect the behavior of ceramic restorations (3).

The occurrence of fractures of ceramic restorations can be associated with inadequate ceramic thickness (4). The properties of the foundation material placed under the ceramic restoration, such as the elastic modulus and resiliency, can also affect strength of the restored unit (5). The brittle nature of ceramics requires an appropriate supporting structure to reinforce and increase the strength of tooth-restoration complex (6).

Studies have indicated a correlation between the

elastic modulus of the supporting structure under adhesive cemented ceramic restoration and strength (3,7). The strength of the indirect restoration may also be influenced by the thickness of ceramic (8) and resin-based materials (9,10). The base material with low elastic modulus seems to favor flexural deformation of the ceramics causing tensile stresses on its internal surface that may lead to fracture. A rigid support may increase resistance of the restored unit because it may reduce stress on the internal surface of the ceramic inlay (3,11). One way to compensate the induced stress caused by the supporting material would be to increase the ceramic thickness when the underlying structure has a lower elastic modulus (3,7).

The finite element method (FEM) is considered an important tool in the study of complex systems (1), as it offers significant information that can assist the identification of sites within the tooth/restoration complex that are more susceptible to failure on either external or internal surface of the models (12). FEM also allows the identification of stress distribution that cannot be evidenced by other methods (13).

The aim of this study was to analyze the influence of cavity depth, ceramic thickness, and resin bases with different elastic modulus on stress patterns of premolars

restored with ceramic inlays by 3-D finite element analysis. The null hypothesis is that these parameters do not affect stress distribution of the tooth/restoration complex.

Method and Materials

Numerical Modeling

The three-dimensional models were developed with the use of an anatomical section of the second maxillary premolar region. The tooth and bone were embedded separately in epoxy resin blocks that were sectioned serially along the tooth long axis with 1-mm-thick section intervals with a precision cutting machine.

The slices were photographed in a standardized manner and each photograph was transferred to the SolidWorks software (Waltham, MA, USA). The external and internal contours of the tooth and bone sections, as well as the dentin and pulp contours were outlined and subsequently assembled. The design of the cusps and occlusal anatomy were refined with the available software tools. This procedure enabled the generation of three-dimensional solid models of the external geometry of the tooth, coronary dentin, pulp and bone that allowed the development of the definitive geometric models. A 0.3 mm-thick periodontal

ligament was generated and a 3-D numerical model of the intact premolar was constructed by assembling all the individual elements that form the tooth and supporting tissues. The components were positioned, aligned, brought together and assembled in an assembly workbench. Modifications were made to obtain the different restored geometric models described in Table 1. In these numerical models, it was established that the resin-based luting cement would be 100- μ m-thick.

Finite Element Modeling

The mesh was composed by parabolic tetrahedral elements and each mathematical model had approximately 230,000 node points and 130,000 solid elements. The level of refinement of the mesh was defined by convergence studies in the Ansys Workbench program (Swanson Analysis Inc., Houston, PA, USA).

Definition of Mechanical Properties

The materials and structures were considered isotropic, elastic and continuous. The elastic modulus (E) and Poisson ratio (ν) were researched in the literature (1,14-20) and are shown in Table 2.

Definition of Boundary and Loading Conditions

The base and the proximal surfaces of the models were constrained, assuming to be fixed in all directions. Each individual 3D model was subjected to the same loading conditions. A compressive static load of 100 N was applied. This value has been used in other studies (21,22) and represents the average chewing forces on the maxillary premolar in function (23). The force was conducted to

Table 1. Numerical models and their characteristics

Model	Depth	Material
Ceramic inlays		
C1	1 mm	Ceramic
C2	2 mm	Ceramic
C3	3 mm	Ceramic
Cavity bases and ceramic inlays		
R1C1a*	2 mm	CR (1 mm) and ceramic (1 mm)
R1C1b**	2 mm	CR (1 mm) and ceramic (1 mm)
R1C1c***	2 mm	CR (1 mm) and ceramic (1 mm)
Cavity bases and ceramic inlays		
R1C2a*	3 mm	CR (1 mm) and ceramic (2 mm)
R1C2b**	3 mm	CR (1 mm) and ceramic (2 mm)
R1C2c***	3 mm	CR (1 mm) and ceramic (2 mm)
Cavity bases and ceramic inlays		
R2C1a*	3 mm	CR (2 mm) and ceramic (1 mm)
R2C1b**	3 mm	CR (2 mm) and ceramic (1 mm)
R2C1c***	3 mm	CR (2 mm) and ceramic (1 mm)

*Composite resin (CR) with low elastic modulus. **Composite resin with medium elastic modulus. ***Composite resin with high elastic modulus.

Table 2. Mechanical properties assigned to dental tissues and restorative materials

Tissue/Material	E	ν	Reference
Enamel	72.7 GPa	0.33	Habelitz et al. (14)
Dentin	18.6 GPa	0.31	Craig and Peyton (15)
Pulp	0.002 GPa	0.45	Lin, Chang and Ko (16)
Periodontal ligament	0.05 GPa	0.45	Rees and Jacobsen (17)
Cortical bone	13.7 GPa	0.3	Ko et al. (18)
Trabecular bone	1.37 GPa	0.3	Ko et al. (18)
Ceramic	96 GPa	0.25	Dong and Darvell (19)
Luting cement	8.3 GPa	0.24	Magne et al. (1)
Composite resin a	5 GPa	0.3	Sabbagh et al. (20)
Composite resin b	13.5 GPa	0.3	Sabbagh et al. (20)
Composite resin c	22 GPa	0.3	Sabbagh et al. (20)

two points located on the internal surface of the buccal and palatal cusps at a 45° angle. The load applied at each point corresponds to the decomposition of the total load of 100 N on the X- and Y-axis.

Processing and Post-processing

Processing was performed with Ansys Workbench program and the analysis of stress distribution was qualitatively performed with von Mises stress diagrams.

Validation

The validation process certifies that the numerical model has the same mechanical behavior as a natural tooth tested under the same *in vitro* conditions, which assures the reliability of the results of the computational simulation (5). Validation was performed by comparison of the load versus displacement graphs of the experimental and numerical data. The experimental and numerical curves are shown in Figure 1. The similar behaviors of both gave good support to the validity of the model. The graphs were obtained from compressive strength testing of intact premolar specimens and from computational simulation of a representative model of these specimens. The numerical model represented the specimens used in the compressive test: intact and with the same structures, shape and dimensions of the tested models used in the study. The embedding material used in the compressive test was also simulated and after validation replaced by the cortical and trabecular bone.

L.B. Durand et al.

Results

The von Mises stress patterns varied among the models and a distinct stress distribution was observed.

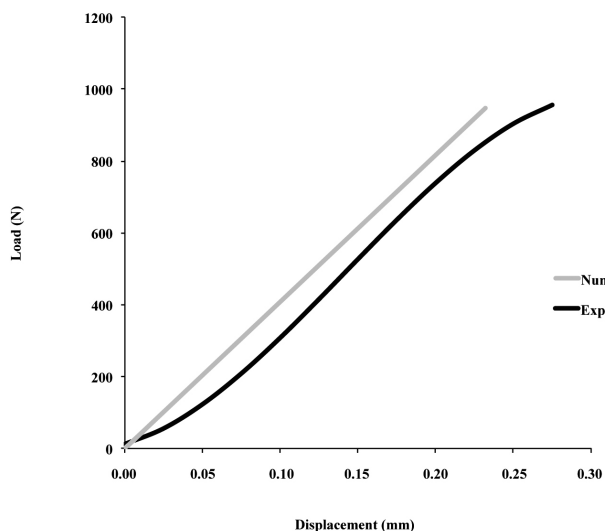


Figure 1. Graph showing validation data: experimental and numerical axial load versus displacement curves.

The qualitative analysis was focused on the cavity floor, internal surface of the inlays, luting cement and resin bases. Figures 2A, 2B and 2C show the von Mises stress distribution on the internal surface of ceramic inlays of numerical models restored with 1 mm, 2 mm and 3 mm-thick inlays, respectively (C1, C2 and C3). The cavity depth and ceramic thickness had an impact on stress distribution of these models. C1 showed maximum stress values at the center of the internal surface of the restoration (Fig. 2A), C2 presented a more favorable stress distribution compared to C1 (Fig. 2B), and C3 demonstrated best results with lower

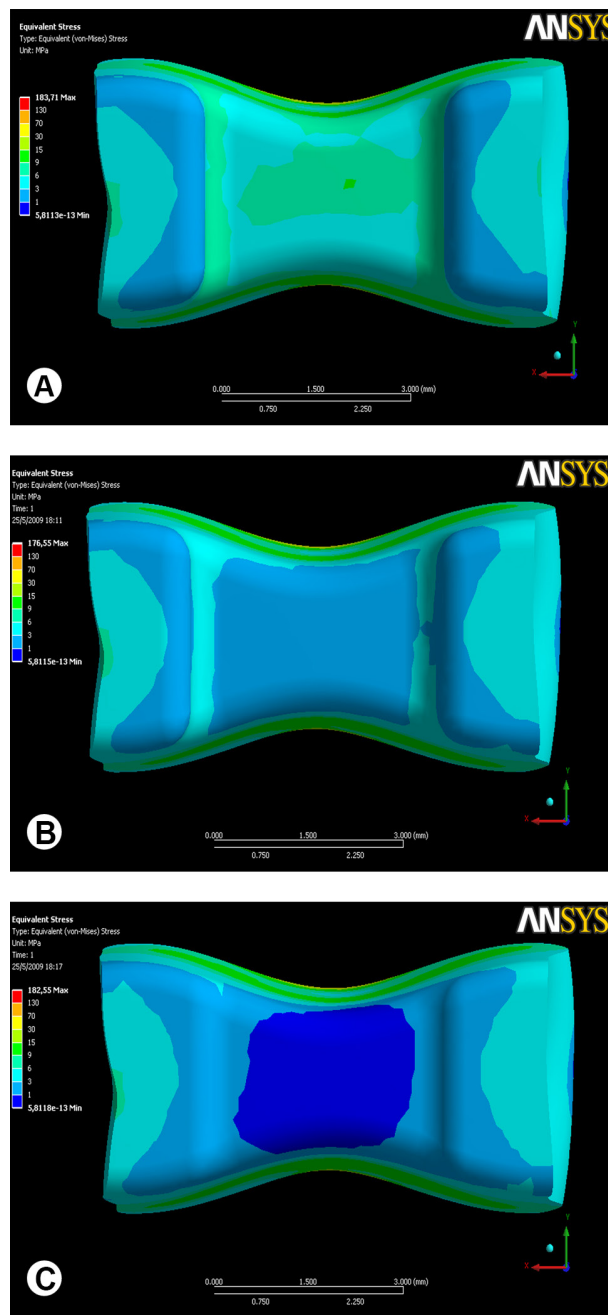


Figure 2. von Mises stress distribution on internal surface of ceramic inlay of numerical model C1 (A), C2 (B) and C3 (C).

von Mises stress values at the center of the internal surface of the ceramic inlay (Fig. 2C).

Figures 3-7 show the stress pattern on the internal surface of the ceramic inlays of models restored with the combination of composite bases and ceramic inlays (R1C1, R2C1, R1C2). The ceramic thickness varied among these models and the von Mises stress diagrams showed that the numerical models with 1-mm-thick inlays (R1C1 and R2C1) combined with composite bases with low elastic modulus (a) had higher stress concentration on the internal surface of the ceramic inlay (Figs. 3 and 4) when compared with models with 1-mm-thick ceramic inlays and medium and high elastic modulus bases (Figs. 5 and 6).

The qualitative analysis also demonstrated that the 2-mm-thick inlays (Fig. 7) presented a more favorable stress pattern than the 1-mm-thick (Figs. 5-6) despite the elastic modulus of the composite base.

In cavity configurations with 2- and 3-mm-deep occlusal boxes, the best stress distributions was found

for models restored exclusively with ceramic material (Figs. 2B and 2C). However, when considering situations in which the resin bases were used, the most favorable

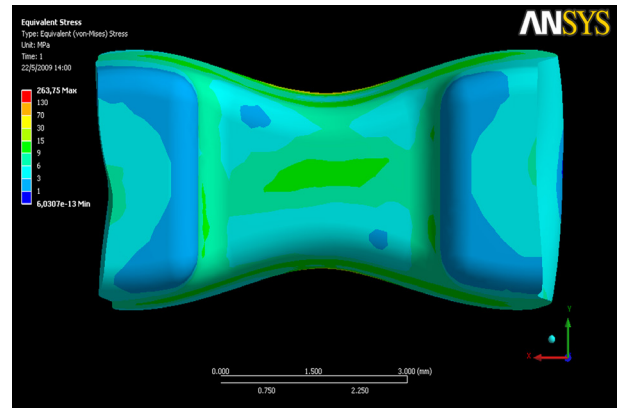


Figure 3. von Mises stress diagrams on internal surface of ceramic inlay of numerical model restored with combination of 1 mm-thick composite resin with low elastic modulus and 1mm-thick ceramic inlay - R1C1a.

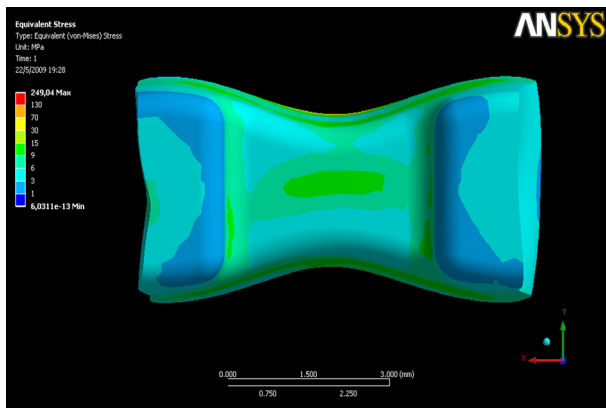


Figure 4. von Mises stress diagrams on internal surface of ceramic inlay of numerical model restored with combination of 2 mm-thick composite resin with low elastic modulus and 1mm-thick ceramic inlay - R2C1a.

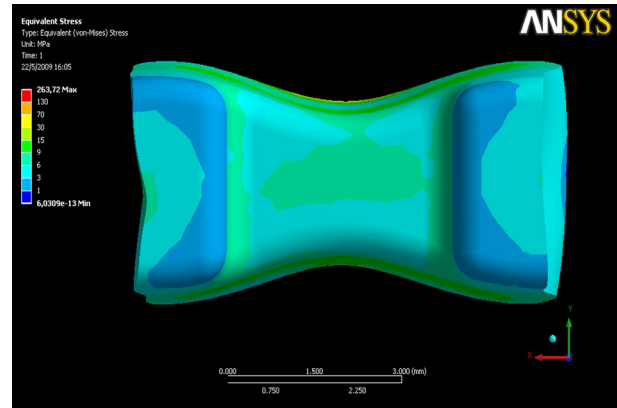


Figure 5. von Mises stress diagrams on internal surface of ceramic inlay of numerical model restored with combination of 1 mm-thick composite resin with high elastic modulus and 1 mm-thick ceramic inlay - R1C1c.

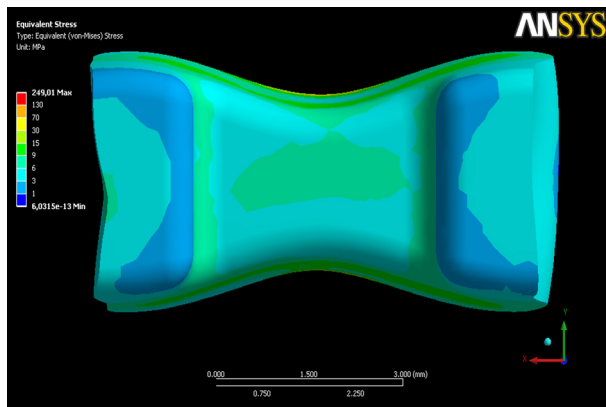


Figure 6. von Mises stress diagrams on internal surface of ceramic inlay of numerical model restored with combination of 2 mm-thick composite resin with high elastic modulus and 1 mm-thick ceramic inlay - R2C1c.

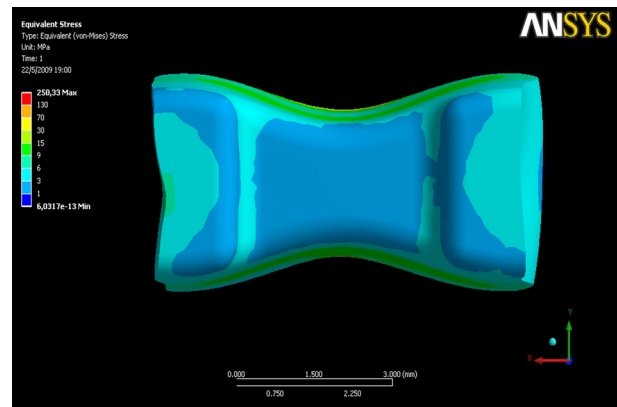


Figure 7. von Mises stress diagrams on internal surface of ceramic inlay of numerical model restored with combination of 1 mm-thick composite resin with high elastic modulus and 2mm-thick ceramic inlay - R1C2c.

Stress distribution of ceramic inlays - a FEA

stress distribution was found for model R1C2c, in which a 1-mm-thick resin base layer with high elastic modulus was used in combination with 2-mm-thick ceramic inlay (Fig. 7).

Discussion

In the present study, qualitative analysis of stress distribution was performed using von Mises stress diagrams. It should be understood that von Mises stress is essentially an aggregated stress (5) which combines tensile, compressive and shear stresses (24). Although qualitative analysis may predict the possibility of damage (21), the total strength of the restored model was not evaluated in this study. Therefore, the results cannot be directly compared with maximum principal stress FEA, since strength was not measured and no distinction was made between tensile and compressive stress. In addition, finite element method has limitations that are peculiar to simulation computer studies; for instance, the properties of the tested materials were considered isotropic, continuous and elastic, which differs from the clinical situations (22).

Validation and optimization of models are important for the reliability of FEM studies. The numerical models used in the present study were constructed based on the intact validated model. The structures, properties, boundary conditions and anatomical characteristics were preserved. There was no need for new validation tests, since once the validity of the model was proven, a wide range of studies can be performed and only significant changes require new experimental validation (25).

Perfect adhesion between the interfaces was assumed. This procedure was adopted for simplification purposes. The interfacial stress between tooth structures and restorative materials was not considered in this study, future research should include variation in loading and interfacial conditions. A 100 N load was selected because it is within the range of loads commonly applied to maxillary premolars and it has been widely used in other studies (22,24).

In this study the null hypothesis was rejected. The presence of resin bases, their elastic modulus and different ceramic thickness affected stress distribution of tooth/restoration complex. With respect to ceramic thickness, higher ceramic thickness lead to a decrease of stress concentration upon the cavity floor, ceramic inlay and luting cement. These results are in agreement with previous studies that associate the occurrence of fractures of ceramic restorations and inadequate thickness (2,4,8).

The highest stress concentration on the internal part of the inlay was observed in models with 1-mm ceramic thickness, particularly those with resin bases that had low elastic modulus. As the thickness increased from 1 mm to 2 mm and 3 mm, the stresses at the base of the ceramic inlay decreased considerably, which is in agreement with

Ona et al. (9).

The elastic modulus of the material that will support the ceramic restoration should be assessed when considering the use of base materials or selecting a material for a buildup. Materials with lower elastic modulus may lead to decreased strength of the restoration (7) and result in increased stress concentration in regions adjacent to it (25). In models where the base material had lower elastic modulus, there was greater stress concentration on the ceramic.

The models that were restored exclusively with ceramics showed better behavior. However, when analyzing the models with composite resin bases, those with an elastic modulus of 13.5 GPa (b) and 22 GPa (c) had better stress distribution than the models with elastic modulus of 5 GPa (a). This result is in agreement with other studies that believe that the bases are not suitable for ceramic support since they promote flexural deformation and subsequent stress formation inside the ceramics that fracture due to their low tensile strength (3,10,23).

The present study analyzed stress distribution with FEM in 3D models. The von Mises stresses diagrams were observed on ceramic inlays, cavity floor, luting cement and cavity bases. The results demonstrated that the models restored exclusively with ceramic material showed better stress distribution than the models restored with ceramic and composite bases and that thicker ceramic restorations tend to have more favorable stress distribution, particularly when bonded directly onto the cavity, without intermediate materials. However, there are few studies that have assessed the combination of these materials. Further studies should investigate the influence of factors such as polymerization shrinkage, thermal and hygroscopic expansion, microleakage and degradation of the composite resin substructure.

In situations in which the use of base materials is inevitable one should prefer composite resins with high elastic modulus and reduced thickness.

Resumo

O objetivo do estudo foi avaliar o efeito da profundidade da cavidade, da espessura da cerâmica e da presença de bases de resina, com os diferentes módulos de elasticidade na distribuição de tensões de von Mises em inlays cerâmicos. Modelos geométricos tridimensionais foram desenvolvidos com o software SolidWorks. As diferenças entre os modelos foram: a profundidade da parede pulpar, a espessura da cerâmica e a presença de bases de resina composta com diferentes espessuras e módulos de elasticidade. Os modelos geométricos foram engastados nas superfícies proximais e base do osso maxilar e uma carga de 100 Newton foi aplicada. O padrão de distribuição de tensões foi analisado com diagramas de tensão de von Mises. O valor de tensão máxima de von Mises foi variável entre os modelos e situou-se na faixa entre 176 e 263 MPa. O maior valor foi encontrado nos modelos restaurados com bases de resina composta de 1 mm e inlay cerâmico de 1 mm de espessura. Valores intermediários (249-250 MPa) ocorreram nos modelos com bases de resina composta

de 2 mm e inlays de 1 mm de espessura e nos modelos com bases de resina composta de 1 mm e inlays de 2 mm. Os menores valores foram observados nos modelos restaurados exclusivamente com inlay cerâmico (176-182 MPa). Verificou-se que inlays com maior espessura distribuem o estresse de forma mais favorável e bases com baixo módulo de elasticidade aumentam a concentração de tensões na superfície interna do inlay de cerâmica. O aumento da espessura do material cerâmico tende a apresentar uma distribuição de tensões mais favorável, principalmente quando cimentadas diretamente sobre o preparo cavitário, sem a existência de materiais intermediários. Em situações em que o emprego de materiais de base é necessária, deve-se preferir resinas compostas com alto módulo de elasticidade e espessura reduzida.

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