

Examination of stress distributions on Class V restorations using nanohybrid resin composite: A 3D finite element stress analysis

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Abstract

Aim: The aim of this study was to investigate and compare the distribution of stress zones in composite resins and dental tissues applied to different-sized Class V cavities in the cervical region of the tooth as a result of the forces acting on the tooth in a computer environment using the finite element method.

Methodology: The extracted lower first molar tooth was scanned and recorded with a dental tomography device. Images were obtained as DICOM files, and these files were imported into the Mimics 12.00 program. In this program, a 3D image of the tooth was created and converted to Standard Tessellation Language (STL) files. The obtained STL files were transferred to the Geomagic Design X program, and Standard for the Exchange of Product Model Data (STP) files were created. The SolidWorks program was used to create different sizes of Class V cavity preparation, restorative material layers, adhesive material layers, and periodontal tissues. Finally, a finite element (FE) model was created in the ABAQUS program, and stress distributions were analyzed.

Results: When the depth was kept constant and the width was increased, the amount of stress on the enamel tissue decreased, while the amount of stress on all other tissues and the restorative material increased. When the width was kept constant and the depth was increased, the amount of stress on the restorative material, adhesive layer, and cortical bone increased, while the amount of stress on the enamel layer, dentin layer, periodontal ligament, and trabecular bone decreased.

Conclusion: Based on the values found in the study, the model that produced the least stress on the restorative material was the model with the least depth and width. However, the stress accumulation in the enamel tissue was higher in this model compared to the other models. As a result, the lifespan of restorative materials may be longer in cavities prepared more shallowly and narrowly during the preparation phase.

Keywords: Finite element analysis, nanohybrid, composite, Class V, stress distribution, Von Mises stress

Introduction

A carious lesion is the result of a chemical event in which certain bacteria present in dental plaque and in the mouth coat the affected area, produce acid from fermentable carbohydrates and lead to the localized dissolution of dental tissues. When the environment on the enamel surface is acidic, calcium and phosphate dissolve from the tooth tissues, resulting in the so-called "white spot lesion" (1, 2). The caries process and tooth erosion are a balance between pathological and protective factors. When pathological factors are stronger, carious lesions progress rapidly; however, early intervention can prevent caries formation and progression (3, 4). Restorative materials to be used in dental caries or tooth erosion should be carefully selected. This reduces the growth of carious tissues and periodontal diseases. Appropriate material selection also leads to less stress accumulation in dental tissues as a result of forces (5). Stress distributions and biofilm layers that are not in accordance with normal biomechanics cause the restoration to come out of the cavity, secondary caries formation as a result of leakage problems in the restoration, and retention problems between the restoration and tooth structure (6, 7). It is recommended that the cavities in the cervical region of the teeth be restored with a micro-filled composite resin or a flowable resin with a low modulus of elasticity (8). A good understanding of intraoral biomechanics and stress distributions is necessary for more successful and long-lasting restorations.

Finite element analysis (FEA) has been a frequently used analysis method in recent years to evaluate and investigate stress distributions and magnitudes in dental structures. Finite Element Stress Analysis (FEA) is a stress analysis method that has the advantage of being applicable to materials with heterogeneous material properties and irregular geometry. Owing to this type of analysis, a better understanding of the reactions and interactions of tissues in the field of dentistry has been achieved (9, 10). In this method, the structures to be analyzed are modeled in the closest way to reality and expressed mathematically. This analysis method, performed in a computer environment, provides more detailed and realistic results than other analyses. Today, with the production of very powerful computers, the use of this method has become widespread. In the FEA method, the stress distribution, shape changes, and magnitudes of the stress that occur due to the application of force in the specified intensity and direction are analyzed in the model created in the computer environment (9). When performing Finite Element Stress Analysis, the Young's Modulus and Poisson's ratio of the materials to be transferred to a computer environment must be known. This analysis method can be performed using two-dimensional or three-dimensional models. The two-dimensional analysis method is easier to apply in a computer environment and does not require very advanced, well-equipped computer systems. However, when stress analysis is performed on

tissues with complex geometry, the 2-dimensional analysis method cannot provide sufficiently accurate and precise results. In the analysis of complex structures, the three-dimensional analysis method is used to obtain results closer to reality; however, this method is more time-consuming and requires experienced engineers and advanced computers (9, 11). Meijer and Clelland reported that the success of the 3D Finite Element Stress Analysis method increases or decreases in direct proportion to the number of elements and nodes in the models. However, increasing the number of elements and nodes requires more powerful computer hardware and increases the analysis time (12, 13)

Most patients visiting the dentist have abrasions, caries, or restorations in the cervical regions of the teeth. The aim of this study was to investigate and compare the distribution of stress zones in composite resins and dental tissues applied to Class V cavities of different sizes in the cervical region of the tooth as a result of the forces acting on the tooth using the finite element stress analysis method.

The null hypothesis of our study was that the stress areas on the dental tissues and restorations adjacent to the cavity in the cervical regions of the teeth, as a result of the forces on the occlusal part of the teeth, do not depend on the width and depth of these cavities.

Materials and Methods

The computer-aided software and programs used in our study for the finite element stress analysis are shown in Figure 1.

The extracted mandibular first molar tooth with no loss of material and no caries on the surface was scanned and recorded using a dental tomography device. The extracted tooth was kept in saline solution until the day of scanning with the cone-beam computed tomography (CBCT) (Morita 3D Accuitomo 170, J Morita Mfg. Corp., Kyoto, Japan). The maximum time the teeth were kept out of the mouth was three months; after removal from the solution, the attachments on the surface were removed with pumice. The imaging volume was a cylinder with a diameter of 40 mm and height of 40 mm at the center of rotation of the X-ray. Images were acquired using the standard parameters of 90 kVp (X-ray tube voltage), 5 mA (electric current rating), and exposure time of 160 qm and 17.5 seconds, which can be varied for different samples. After the images were obtained as DICOM files, these files were imported into the Mimics 12.0 (Materialise Interactive Medical Image Control System, Leuven, Belgium). Masks were created for each tooth texture and converted to STL files. These STL files were transferred to the Geomagic Design X program (Geomagic Design X 2020.0; Octon Inc, Los Angeles, LA, USA), and STP files were obtained by making necessary arrangements such as smoothing them. These STP files were transferred to the SolidWorks program (SolidWorks Corp., Waltham, MA, USA) and three Class V cavities of different sizes (Model I: 1 mm depth, 4 mm

width; Model II: 1 mm depth, 3 mm width; Model III: 1.5 mm depth, 3 mm width) were prepared, nanohybrid composite resin (VOCO Grandio; VOCO GmbH, Cuxhaven, Germany) material was placed in these cavities and a layer of adhesive material, periodontal ligament (0.2 mm), cortical bone, trabecular bone were formed (Fig. 2) and the obtained elements were transferred to ABAQUS program (2020 Dassault Systems Simulation

Corp., Johnston, RT, USA). Finite Element (FE) model was created using the ABAQUS program.

In the finite element model, the stress zones on the tooth tissue, restorative material, adhesive material, and periodontal tissues as a result of a 600 Newton (N) force acting perpendicular to the ground plane from the occlusal region to the tooth surface were determined and analyzed. The physical properties of the materials required for stress analysis are given in Table 1.

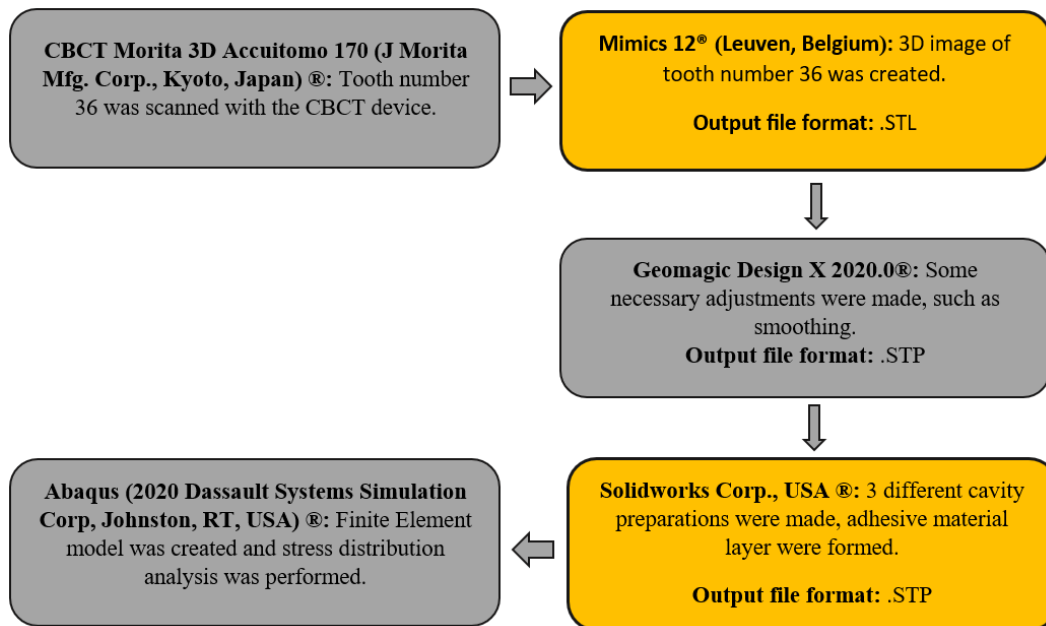


Figure 1. Sequential equipment and software set used for finite element stress analysis.

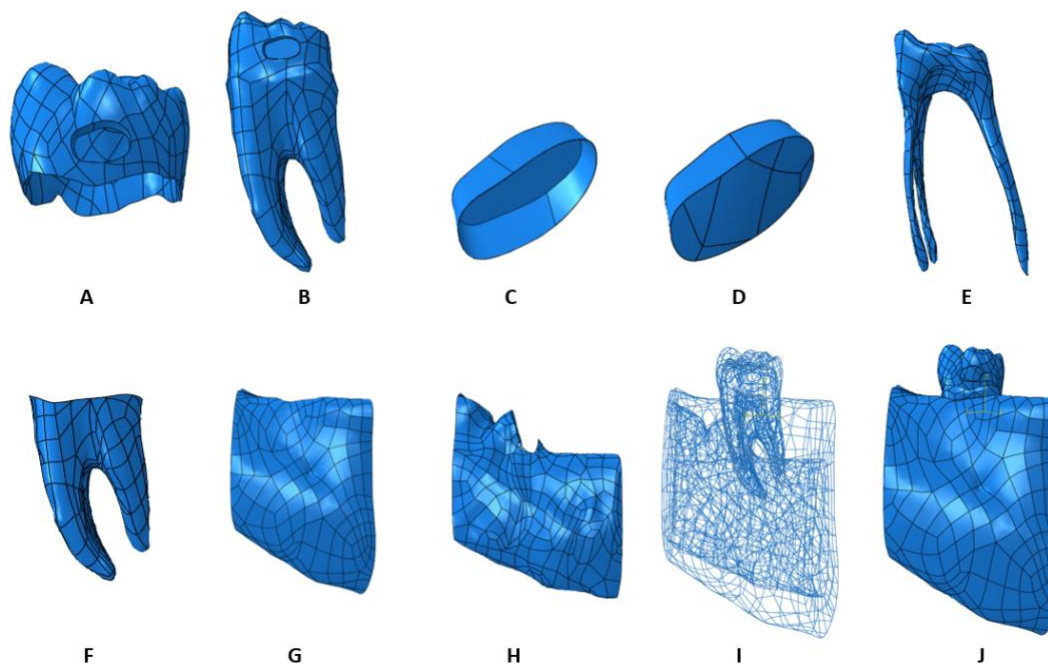


Figure 2. Models created in SolidWorks program. A) Enamel, B) Dentin, C) Adhesive layer, D) Restoration, E) Pulp, F) Periodontal ligament, G) Cortical bone, H) Trabecular bone, I-J) Completed model.

Table 1. Mechanical properties of dental tissues, periodontal tissues and materials used component

Materials	Young Modulus (GPa)	Poisson's Ratio	Tensile Strength (MPa)	Compressive Strength (MPa)	Shear Modulus (MPa)
Nanohybrid composite (VOCO Grandio)	20.4 (14)	0.33 (14)	-	-	
Adhesive system	3.6 (15)	0.28 (15)	-	-	
Dentin	18.6 (16)	0.31 (16)	98.7 (17)	297.0 (17)	
Enamel	84.1 (16)	0.33 (16)	10.3 (17)	384.0 (17)	
Pulp	0.002 (18)	0.45 (18)	-	-	
Periodontal ligament	0.05 (19)	-	-	-	
Trabecular bone	Ex 1148 (20)	V _{xy} 0.055 (20) V _{yz} 0.010			G _{xy} 4.850 (20)
	Ey 210 (20)	V _{xz} 0.322 (20) V _{yx} 0.010	-	-	G _{yz} 5.700 (20)
	Ez 1148 (20)	V _{zy} 0.055 (20) V _{zx} 0.322			G _{xz} 5.700 (20)
Cortical bone	Ex 12.600 (20)	V _{xy} 0.300 V _{yz} 0.253			G _{xy} 68 (20)
	Ey 12.600 (20)	V _{xz} 0.253 (20) V _{yx} 0.300	-	-	G _{yz} 68 (20)
	Ez 19.400 (20)	V _{zy} 0.390 (20) V _{zx} 0.390			G _{xz} 434 (20)

Results

Results for Model I (1 mm depth, 4 mm width):

In this model, the most stressed structures as a result of occlusal force were dentin, enamel, adhesive material, restoration, trabecular bone, and cortical bone, respectively. The structure subjected to the least stress was the periodontal ligament (Table 2).

In enamel, the enamel tissue in the cervical region adjacent to the cavity was the most stressed area. In dentin, the highest stress was observed on the inner surfaces of the mesial and distal roots facing each other. The highest stress in the restoration was observed in parts of the restoration adjacent to the occlusal and pulpal walls (Fig. 3).

Results for Model II (1 mm depth, 3 mm width):

In this model, the most stressed structures as a result of occlusal force were dentin, enamel, cortical bone, trabecular bone, adhesive material, and restoration, respectively. The structure subjected to the least stress was the periodontal ligament (Table 2). In the enamel

tissue, the highest stress was observed in the enamel in the occlusal region of the tooth where the force was applied and in the enamel tissue in the cervical region adjacent to the cavity. The highest stress was observed in dentin on the inner surfaces of the mesial and distal roots facing each other, as in Model I. In the restoration, the area with the highest stress was observed in the mesial area adjacent to the occlusal wall of the cavity (Fig. 4).

Results for Model III (1.5 mm depth, 3 mm width):

In this model, the most stressed structures as a result of occlusal force were dentin, enamel, restoration, adhesive material, cortical bone, and trabecular bone, respectively. The structure subjected to the least stress was the periodontal ligament (Table 2). In the enamel, the most stressed areas were the enamel margins in the central fossa and the enamel tissue in the cervical region adjacent to the cavity. The highest stress was observed in dentin on the inner surfaces of the mesial and distal roots facing each other. The highest stress in the restoration was observed in parts of the restoration adjacent to the occlusal and pulpal walls (Fig. 5).

In the prepared Class V models, when the depth was kept constant, and the width was increased, the amount of stress on the enamel tissue decreased, whereas the amount of stress on all other tissues and the restorative material increased. When the width was kept constant

and the depth was increased, the amount of stress on the restorative material, adhesive layer, and cortical bone increased, while the amount of stress on the enamel layer, dentin layer, periodontal ligament, and cortical bone decreased.

Table 2. Amounts of stress in the tissues, restoration, and adhesive material

Layers	1 mm - 4 mm	1 mm - 3 mm	1.5 mm - 3 mm
Enamel	9.013e + 01	9.782e + 01	9.250e + 01
Dentin	2.024e + 02	1.863e + 02	1.619e + 02
Adhesive material	2.078e + 01	6.621e + 00	1.373e + 01
Restoration	1.419e + 01	5.465e + 00	1.452e + 01
Periodontal ligament	2.101e + 00	2.069e + 00	2.048e + 00
Cortical bone	1.144e + 01	1.111e + 01	1.137e + 01
Trabecular bone	1.253e + 01	1.108e + 01	1.020e + 01

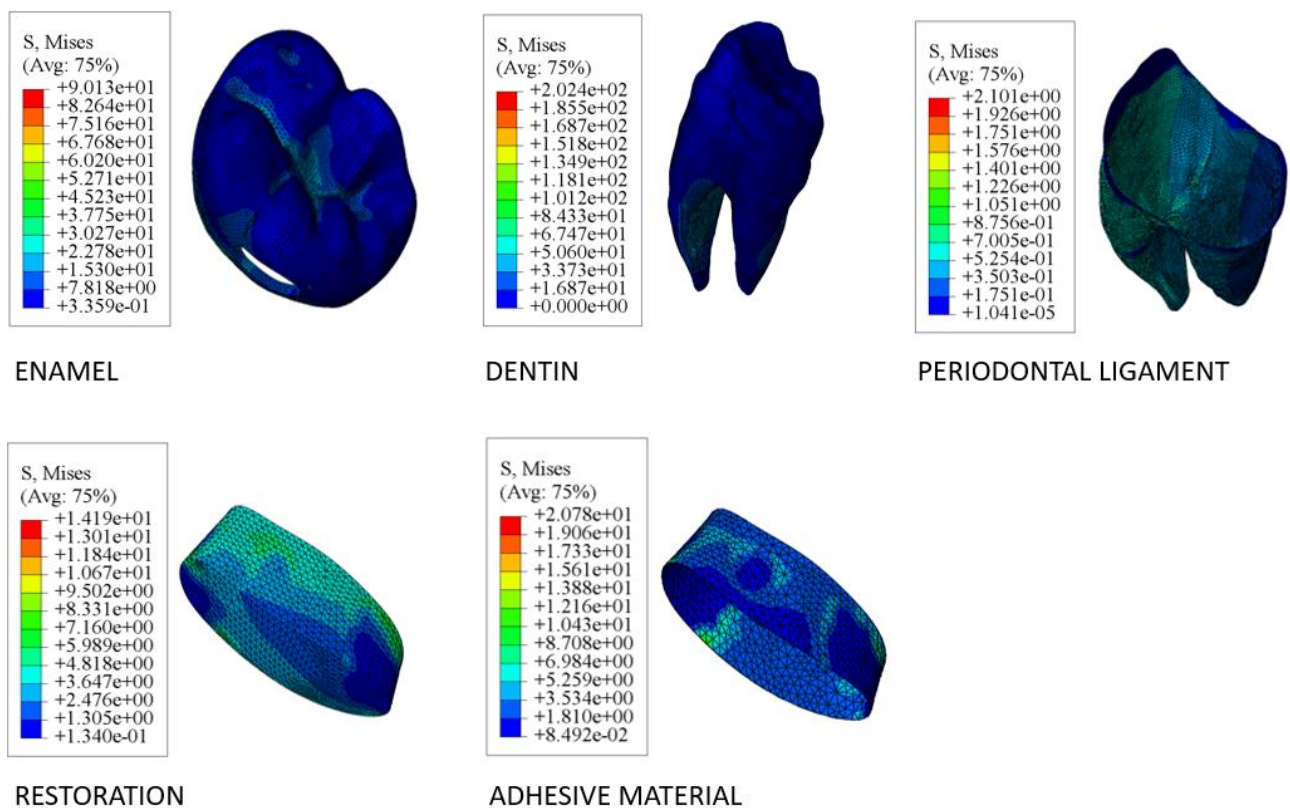


Figure 3. Stress distribution regions on the tissues and restoration of Model I.

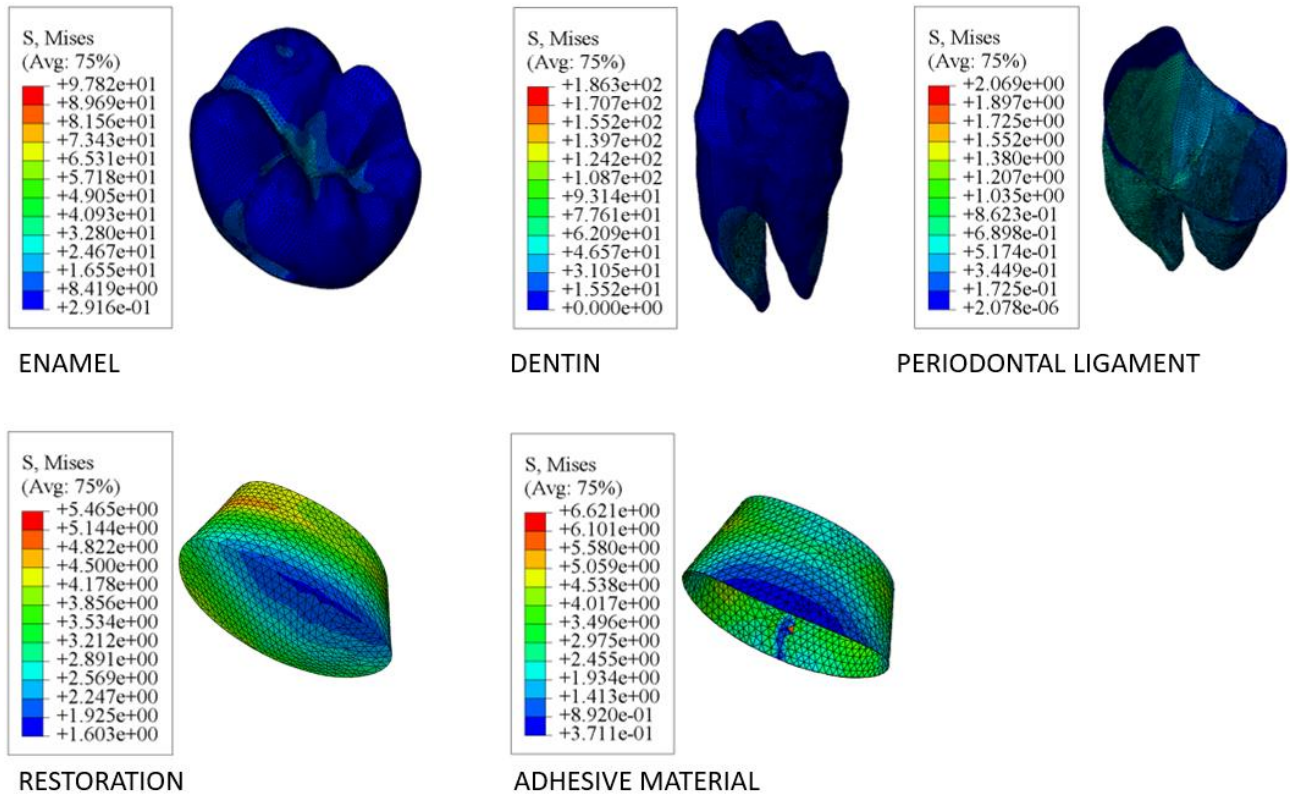


Figure 4. Stress distribution regions on the tissues and restoration of Model II.

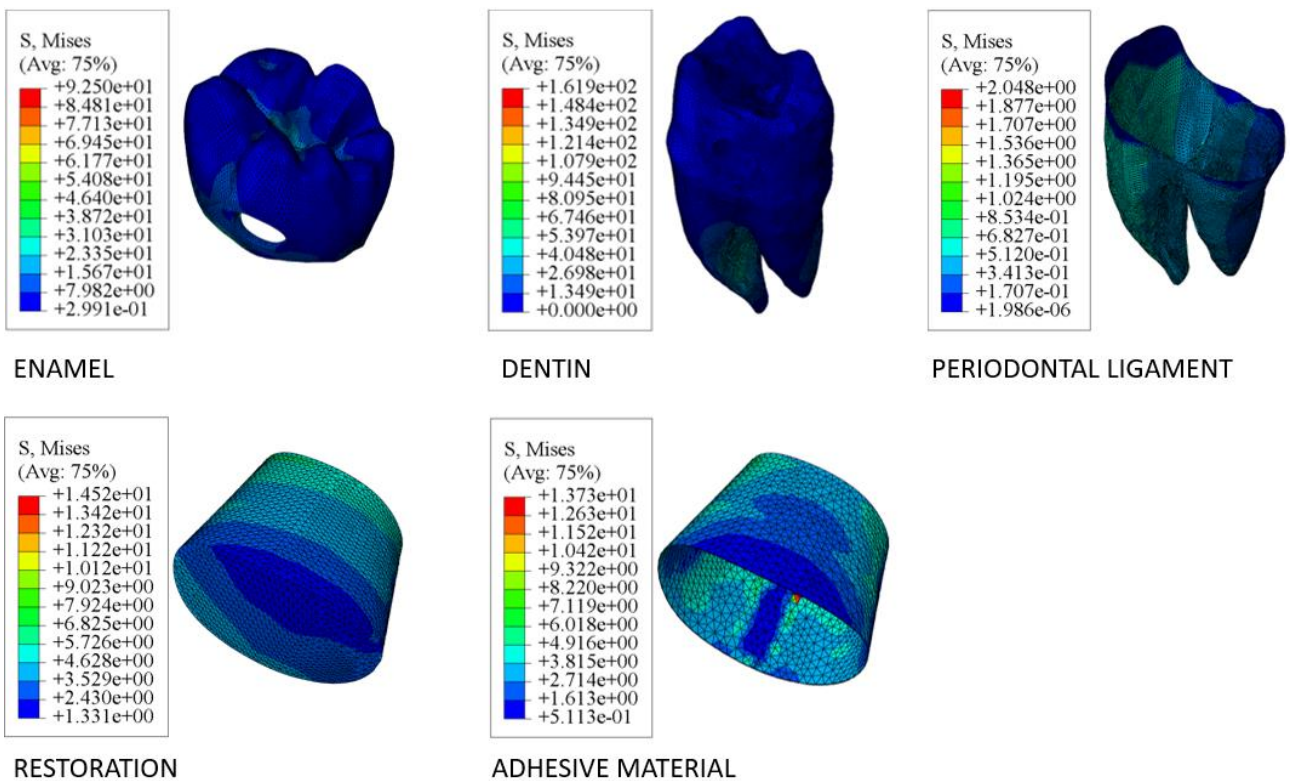


Figure 5. Stress distribution regions on the tissues and restoration of Model III

Discussion

In our study, three different sizes of Class V cavity models were created in the lower 1st molar teeth, and the stress areas occurring in the dental tissues and restorations as a result of occlusal forces on these models were compared. The hypothesis that the stress areas on the dental tissues and restorations adjacent to the cavity in the cervical regions of the teeth as a result of the forces on the occlusal part of the teeth do not depend on the width and depth of these cavities was rejected.

Meijer et al. stated in their study that the two-dimensional analysis method does not give accurate results (12). In many studies, it has been stated that the three-dimensional finite element stress analysis method gives more consistent and accurate results (21-23). In addition, Kamposiora et al. stated that the technique would be simplified by reducing the data of three-dimensional materials to two dimensions so that high-capacity computers would not be needed and the cost would be reduced, but 3-dimensional analysis methods should be used to obtain more accurate results (24). In our study, we used the 3D stress analysis method to obtain more accurate results.

In 2006, Mesquita et al. reported that composites with low elastic modulus would deform more under functional and parafunctional stresses, resulting in fracture of the tooth structure, weakening of the connection between the tooth tissues and the restoration, and causing postoperative sensitivity and secondary caries (25).

In a study conducted by Yaman et al. in 2003, they scanned the maxillary central tooth with a dental tomography device, transferred it to the computer environment, and opened a Class V cavity on the tooth surface. While restoring the cavities, they used composite and compomer materials from different brands and examined and compared the stress magnitudes and distributions by finite element stress analysis. A force of 200 Newton was applied at an angle of 26 degrees with the long axis of the maxillary central tooth, and loads of 100 Newton and 400 Newton were applied at 90 degrees and 0 degrees to represent bruxism and traumatic load. As a result of the study, it was understood that larger cavity preparations cause greater stresses in dental tissues and that the stresses in restored teeth are inversely proportional to the modulus of elasticity of the restorative materials. Among the composites and compomers used in the study, Filtek Z100 brand composite was the most superior to the others (26). In our study, it was concluded that the cavity model with the smallest depth and width had the least stress on the restoration, but the stress on the enamel tissue was found to be higher in this model than in the other models.

Goel et al. prepared and restored three cavity models of different sizes and examined the stress distribution using the finite element stress analysis method in a computer environment. As a result of the examination, they concluded that the stress on the

tissues was also high in the model with high tissue loss (27).

Conclusion

Based on these values in the study, the model with the least stress on the restorative material was the model with the least depth and width. However, the stress accumulation in the enamel tissue was higher in this model compared to the other models. As a result, the lifespan of restorative materials may be longer in cavities prepared shallower and narrower during the preparation phase.

Disclosures

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