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Examination of stress distribution on Class I cavity restored using amalgam and bulk-fill composite: A 3D finite element stress analysis

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Abstract

Aim: The aim of this study was to examine the stress distribution on the tooth structure, restorative materials, and periodontal tissues prepared in a computer environment as a result of the forces acting on the mandibular premolar tooth surface, using the finite element stress analysis method.

Methodology: The extracted mandibular premolar tooth was scanned with a dental tomography device and recorded. Images were obtained as digital imaging and communications in medicine (DICOM) files, which were transferred to the Mimics 12.00 program. This program was used to create a 3D image of the tooth, which was converted into a Standard Tessellation Language (STL) file. The resulting STL files were transferred to the Geomagic Design X program, some necessary adjustments, such as smoothing, were made, and Standard for the Exchange of Product Model Data (STP) files were created. The STP files were transferred to the SolidWorks program and Class I cavity preparation, restorative material layers, adhesive material layers, and periodontal tissues were created. Finally, the finite element (FE) model was created in the ABAQUS program, and the stress distributions were analyzed.

Results: In the model restored with bulk-fill, compared to the model restored with amalgam, the amount of stress on dentin was found to be higher, while the amount of stress on cortical bone, trabecular bone, periodontal ligament, and enamel was found to be lower. In both models restored with bulk-fill composite and amalgam, the structure exposed to the most stress was the enamel layer, while the structure exposed to the least stress was the periodontal ligament. The amount of stress on the amalgam material was found to be higher than the amount of stress on the bulk-fill composite material.

Conclusion: Amalgam and bulk-fill composite materials are frequently used today in posterior teeth with large cavities. As a result of our study, bulk-fill composite material caused less stress distribution than amalgam in all tissues except dentin tissue.

Keywords: Finite element analysis, amalgam, bulk-fill, Class I, stress distribution, Von Mises stress

Introduction

The success of restorations in dentistry depends not only on chemical, physical, and biological factors. For a successful treatment, the materials and dental tissues to be used must be well-known (1). In the oral cavity, restorations are subjected to stress from masticatory forces and their mechanical strength changes over time. The magnitude and distribution of the forces caused by the muscle tissues and dental structures in and around the oral environment directly affect the prognosis of the treatment applied. Therefore, the material used for restoration should be correctly selected (2). When restorative materials are properly selected, the risk of secondary caries formation, biofilm layers, plaques, and periodontal disease is reduced. In addition, the correct choice of material results in reduced stress accumulation in tooth tissues (3). Abnormal stress distribution on the tooth surface and plaque layers adhering to the tooth surface can lead to cavity separation of the restoration, microleakage problems, and failures such as cavity debonding of the restoration (4, 5).

Amalgams are used for the restoration of posterior teeth and are now widely used in some countries due to their relatively low cost compared to composites (6).

Composite resins have a more aesthetic appearance compared to amalgams. Resin composites are an aesthetic alternative to amalgam. They have been developed to restore teeth to their natural form, and are now widely used. Bulk-fill resin composites with thicknesses of 4-5 mm and can be polymerized in one step. Because the layering technique is less in bulk-fill composites than in composite resins, the restoration time is even shorter (7).

Stress analysis of dental structures has been a topic of interest in recent years to determine the stresses in dental structures and increase the mechanical strength of these structures. The oral cavity is a complex biomechanical system that has limited access. Therefore, most biomechanical studies on the oral environment have been performed in vitro (8). Finite element analysis (FEA) has become an important research method for stress and thermal analysis in some current studies. It is a successful method for analyzing the dynamic, mechanical, and thermal properties of 3D complex structures after they are transferred to the computer environment. FEA is a non-invasive method used to study the effect of forces on biological systems and tissues (9). It also allows the determination of the position, magnitude, and direction of the applied force, because theoretically measurable stress points can also be determined (10). Two types of analyses are commonly used: 2D and 3D modeling. Although 2D modeling is simple and allows the analysis to be performed on a relatively normal computer, it tends to yield less accurate results. However, 3D modeling produces more accurate results (11). The finite element stress analysis method has the advantages of being non-invasive, easily and repeatedly reproducible, minimizes the need for laboratory testing, and can be applied in a short time, even in complex structures. In addition to all the advantages of this method, there are some limitations, such as the difficulties in transferring biological structures to computer programs, the properties of the tissues and materials planned to be used in the study, and the fact that the angle and magnitude of the forces to be applied are completely dependent on the user.

The aim of this study was to investigate the stress distribution points and their magnitudes on the tooth structure, restorative materials, and periodontal tissues prepared in the computer environment as a result of a force of 600 Newton (N) perpendicular to the ground plane from occlusal to the surface of the mandibular 1st premolar tooth using the finite element stress analysis method.

The null hypothesis of this study was that the stress distribution on the tooth structures, restorative materials, and periodontal tissues as a result of the forces on the tooth surface on the computerized model would not differ according to the restorative material used.

Materials and Methods

The software set used for stress distribution and analysis in our study is shown in Figure 1.

The extracted mandibular 1st premolar tooth without loss of material and 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 tooth was kept out of the mouth was three months; after removal from the solution, the attachments on the surface were removed with pumice). Images were captured using the standard parameters of 90 kVp (X-ray tube voltage), 5 mA (electric current value), and exposure time parameters of 160 qm and 17.5 seconds, which can be changed according to different samples. After the images were obtained as DICOM files, these files were imported into the Materialise Interactive Medical Image Control System (Mimics 12.00, Materialise Inc., Leuven, Belgium), and after three-dimensional objects were created, the files were saved in STL format. These files were transferred to the Geomagic Design X software (Geomagic Design X 2020.0; Octon Inc, Los Angeles, LA, USA) and STP files were obtained by making necessary arrangements, such as smoothing them. STP files were transferred to the SolidWorks software (SolidWorks Corp., Waltham, MA, USA) and Class I cavity preparations were made. Bulk-fill composite resin and amalgam material were placed in these cavities, a layer of adhesive material, periodontal ligament (0.2 mm), trabecular bone, and cortical bone were created (Fig. 2), and elements were transferred to the ABAQUS software (2020 Dassault Systems Simulation Corp., Johnston, RT, USA). A finite element (FE) model was created using the ABAQUS.

In the Finite Element model that we created, the stress regions and their magnitudes on the tooth tissue, restorative material, adhesive material, and periodontal tissues as a result of the force acting on the tooth surface were analyzed and examined.

A force of 600 N was applied to the occlusal part of the tooth, perpendicular to the ground plane, to analyze and compare the stress zones and magnitudes in the dental tissues, restorative materials, and periodontal tissues. The physical properties of the materials required for stress analysis are given in Table 1.

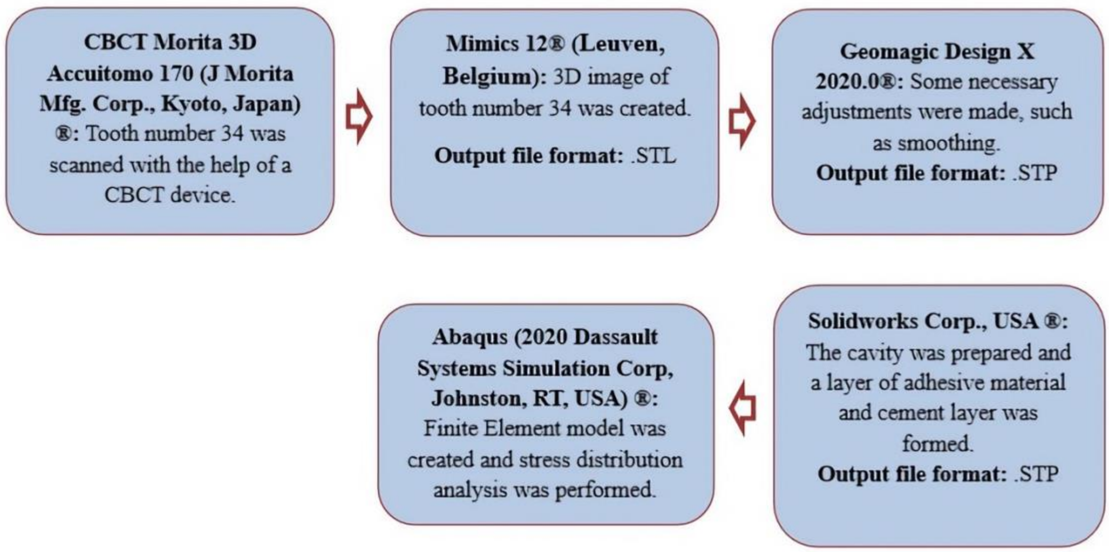

Figure 1. Sequential equipment and software set used for finite element stress analysis

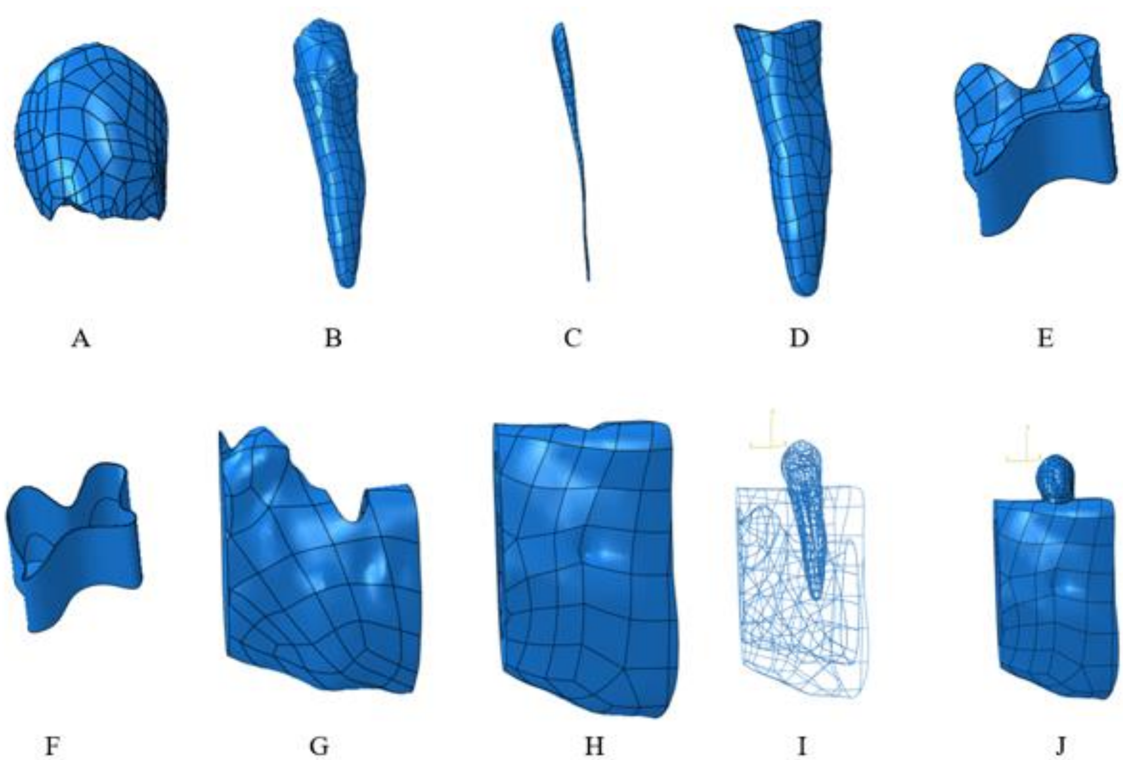

Figure 2. Models created in the SolidWorks program. **A)** Enamel, **B)** Dentin, **C)** Pulp, **D)** Periodontal ligament, **E)** Restoration, **F)** Adhesive material, **G)** Trabecular bone, **H)** Cortical bone, **I-J)** Completed model

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

Materials	Young Modulus (GPa)	Poisson's Ratio	Tensile Strength (MPa)	Compressive Strength (MPa)	Shear Modulus (MPa)
Resin Cement (V1) Variolink II (Ivoclar Vivadent, Schaan, Liechtenstein)	8.3 (12)	0.35 (12)	-	-	
Amalgam	35 (13,14)	0.35 (13,14)	3-58 (15)	45-550(15)	
Bulk-Fill composite	12.0 (16)	0.25 (16)	42 (17)	169.0(17)	
Adhesive system	3.6 (18)	0.28 (18)	-	-	
Dentin	18 .6 (19)	0.31 (19)	98.7 (20)	297.0 (20)	
Enamel	84.1 (19)	0.33 (19)		384.0(20)	
Pulp	0.002 (21)	0.45 (21)	-	-	
Periodontal ligament	0.05 (22)	-	-	-	
Trabecular bone	Ex 1148 (23) Ey 210 (23) Ez 1148 (23)	V xy 0.055 (23) V yz 0.010 V xz 0.322 (23) V yx 0.010 V zy 0.055 (23) V zx 0.322	-	-	Gxy 4.850 (23) Gyz 5.700 (23) Gxz 5.700 (23)
Cortical bone	Ex 12.600 (23) Ey 12.600 (23) Ez 19.400 (23)	V xy 0.300 (23) V yz 0.253 V xz 0.253 (23) V yx 0.300 V zy 0.390(23) V zx 0.390	-	-	Gxy 68 (23) Gyz 68 (23) Gxz 434 (23)

Results

When bulk-fill composite resin material was used to restore the Class I cavity of the model, enamel was the most stressed structure because of the forces acting on the occlusal part of the tooth, followed by the adhesive material, dentin, trabecular bone, restoration, and cortical bone, respectively.

The periodontal ligament was least exposed to stress. In the cavity restored with amalgam, the structure exposed to the highest stress was enamel, followed by dentin, trabecular bone, restoration, cement, and cortical bone. The least stressed structure was again the periodontal ligament.

The amount of stress on dentin was higher in the model restored with bulk-fill than in the model restored with amalgam, while the amount of stress on cortical bone, trabecular bone, periodontal ligament, and enamel was lower (Table 2).

In both the bulk-fill composite and amalgam models, it was concluded that the most stressful areas on the enamel were the edges adjacent to the restoration on the occlusal surface of the enamel, while the least stressful areas were the tubercle ridges. In both models, the most stressed area on the restorations was the central fossa, while these values decreased towards the edges adjacent to the enamel.

In the model restored with bulk-fill, the area where the adhesive was exposed to the most stress was the edges adjacent to the restoration.

The amount of stress on the amalgam material was found to be higher than that on the bulk-fill composite material (Figs 3 and 4).

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

	Bulk-Fill Composite	Amalgam
Enamel	$1.266e+02$	$1.706e+02$
Dentin	$5.912e+01$	$5.366e+01$
Cement - Adhesive	$7.272e+01$	$2.866e+01$
Restoration	$2.606e+01$	$2.942e+01$
Periodontal ligament	$6.737e+00$	$9.415e+00$
Cortical Bone	$1.071e+01$	$1.087e+01$
Trabecular Bone	$3.248e+01$	$3.271e+01$

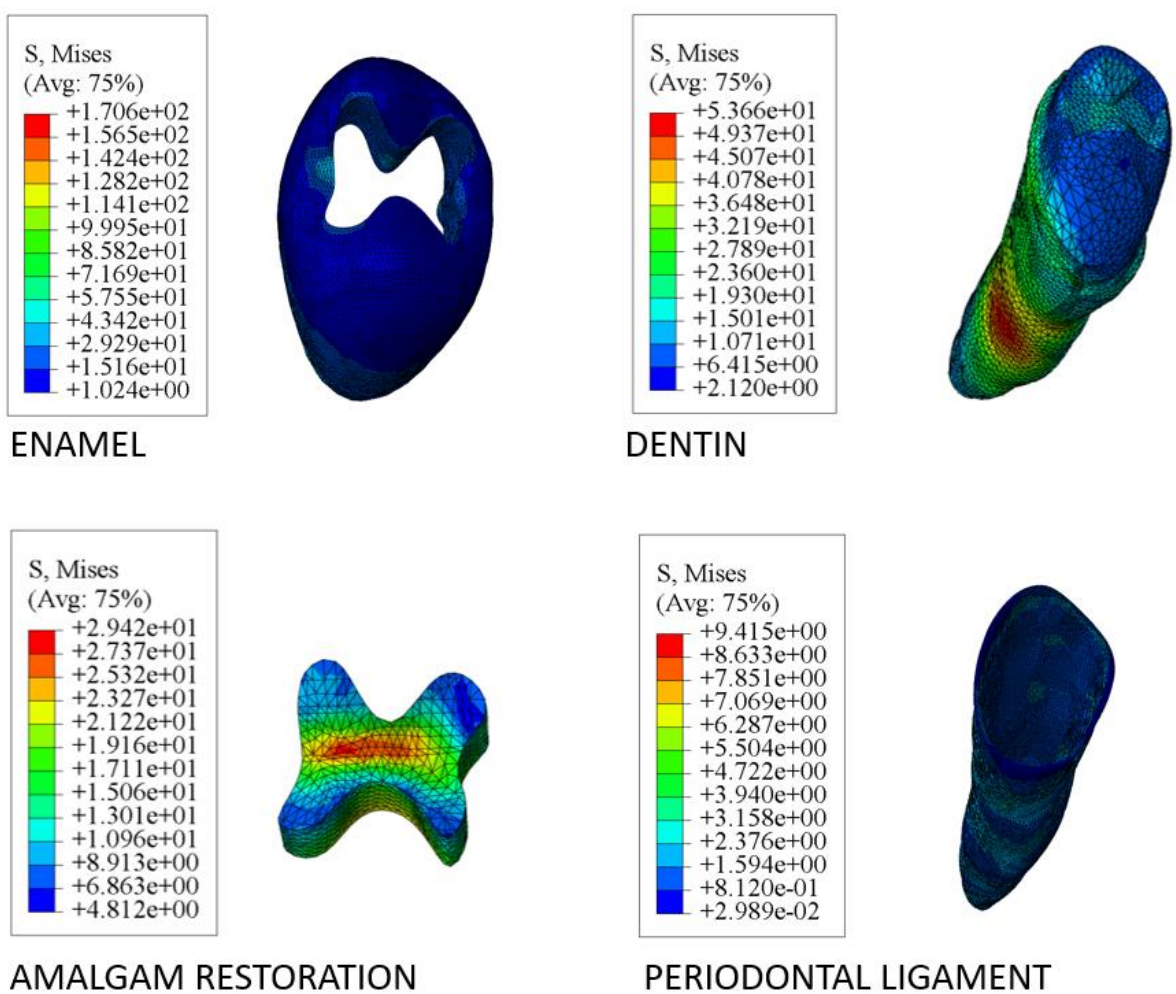

Figure 3. Stress distribution regions on tissues and restoration of the model restored with amalgam

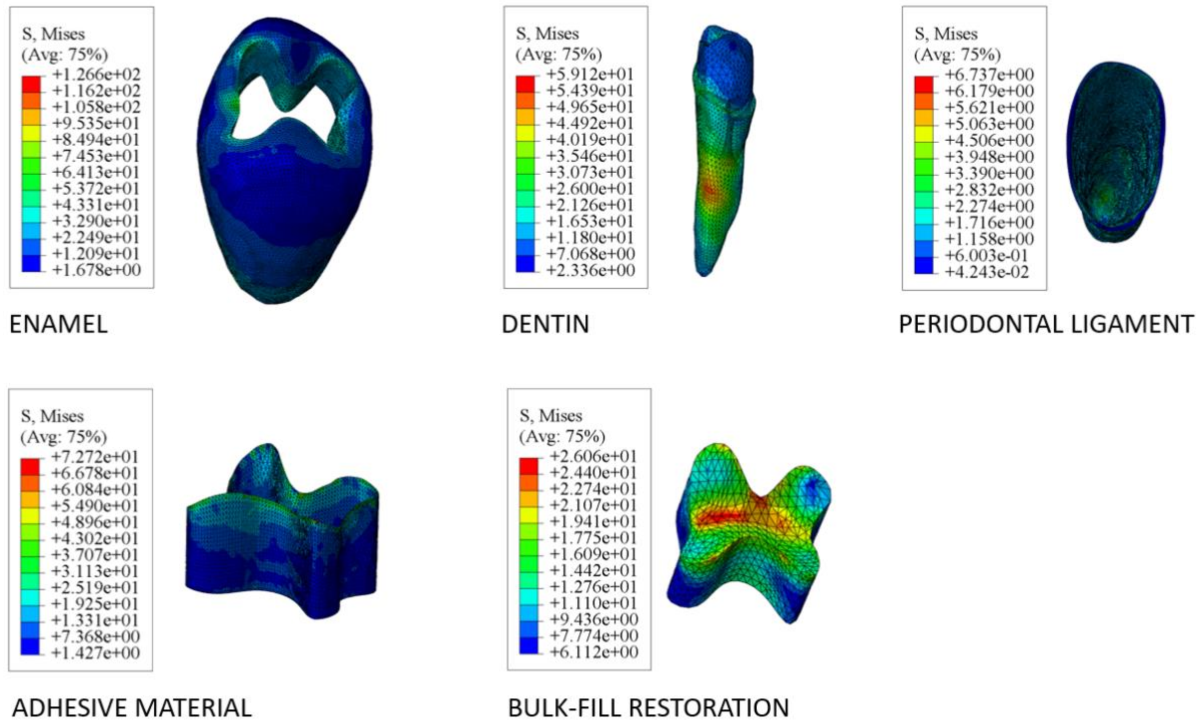

Figure 4. Stress distribution regions on the tissues, restoration, and adhesive material of the model were restored with a bulk-fill composite resin.

Discussion

Finite element stress analysis is important for the biomechanical analysis of tooth structure, periodontal tissues, and restorative materials because it improves the understanding of the behavior of these structures as a result of incoming forces. The application of non-invasive and reproducible tests, such as finite element stress analysis, has facilitated the understanding of the success-failure characteristics of restorative procedures. In our study, amalgam and bulk-fill composites were used as restorative materials to evaluate the material behavior in clinical use, and stress distribution analysis was performed using computerized models. In this study, CBCT images of an extracted mandibular 1st premolar tooth were used to standardize the actual tooth geometry in 3D. The stress distribution in the Class I cavity of the mandibular first premolar tooth restored with amalgam and bulk-fill composites was investigated by comparing them with the 3D finite element stress analysis method.

In a study by Musani et al., the lower first molar was scanned and computerized, and then a Class I cavity was opened on this model and restored with amalgam and composite resin. The stress distributions on this model were analyzed using the finite element stress analysis method. As a result, amalgam and composite resin showed similar stress distributions, but the amount of stress in the dental tissues restored with composite resin was higher. Therefore, it was concluded that teeth restored with amalgam had better stress distribution values than teeth restored with composite resins (24).

Ausiello et al. investigated the stress analysis of bulk-fill resin composites in Class II restorations. In this study, bulk-fill composite restorations exhibited high stress accumulation at the cavity edges against the forces acting on the tooth tissue. Therefore, resin-based bulk-fill composite materials are not recommended for large Class II restorations (25).

In the study by Jiang et al. four 3D molar models were created to make inlay and onlay restorations on vital and nonvital teeth. Composite resin, ceramic, and gold alloy materials were tested in each group. As a result, composite resin onlays reduced the internal stresses much less than the other models and caused less destructive stress on the dental tissues (26).

Iftikhar et al. evaluated the stress distributions at different loads on Class II MOD cavity restored with intact molars and four different restorative materials (ClearFil AP-X Composite Resin, GIC Fuji IX GP, Filtex Z350-XT, Cention N) using finite element analysis. Similar to our study, enamel showed the highest stress accumulation (2).

Conclusion

In our study, we examined the stress distributions on enamel, dentin, restoration, periodontal ligament, trabecular bone, and cortical bone in cavities restored with bulk-fill and amalgam. As a result, the bulk-fill composite material caused less stress distribution than amalgam in all tissues except dentin tissue. The hypothesis that the stress distribution on the tooth structure, restorative materials, and periodontal tissues prepared in the computer environment as a result of the forces on the initial tooth surface would not differ according to the restorative material used was rejected. The data obtained from our study should be supported by more in vivo studies.

Disclosures

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