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JURNAL TEKNOSAINS

Finite element analysis: stress and strain in chitosan composites under varying cavity dimensions

Indonesian title: Analisis elemen hingga: tegangan dan regangan pada komposit kitosan dengan berbagai macam dimensi kavitas

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ABSTRAK

Kegagalan restorasi resin komposit seringkali terjadi akibat pembentukan karies sekunder. Kitosan memiliki potensi antibakteri untuk mengatasi kegagalan restorasi resin komposit tersebut. Penelitian yang ada memiliki keterbatasan, yaitu kurang berfokus pada fungsi biomekanik material restorasi di dalam rongga mulut yang berfungsi secara mekanis. Penelitian ini menggunakan Analisis Elemen Hingga (FEA) untuk mengevaluasi pengaruh kombinasi penambahan kitosan dan dimensi kavitas terhadap distribusi tegangan dan regangan dalam material resin komposit. Model 3-dimensi gigi molar pertama mandibula manusia, yang diperoleh dari pemindaian mikro-CT, disimulasi menggunakan FEA dengan berbagai konsentrasi kitosan (0%, 0,5%, 1,0%, dan 2,0%) dan dua dimensi kavitas (konservatif dan ekstensif). Hasil statistik menunjukkan perbedaan yang signifikan dalam distribusi tegangan dan regangan di seluruh kelompok percobaan. Dimensi kavitas secara signifikan memengaruhi distribusi tegangan dan regangan. Efek penambahan kitosan bersifat sekunder. Penambahan kitosan dalam kasus kavitas ekstensif tidak cukup kuat untuk menghasilkan perubahan yang signifikan secara statistik. Analisis FEA menunjukkan pengaruh geometri kavitas yang jelas terhadap biomekanika: pada kavitas yang luas, material restoratif memberikan penguatan struktural yang unggul, menghasilkan unit komposit yang lebih kaku (tegangan tinggi, regangan rendah) dan deformasi cusp yang terbatas; sementara pada kavitas konservatif, struktur komposit menunjukkan respons yang sangat fleksibel terhadap pembebanan (tegangan rendah, regangan tinggi),

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bahkan dengan marginal ridge yang dipertahankan. Konsentrasi tegangan berada pada area servikal gigi, khususnya pada cementoenamel junction (CEJ).

Keywords: *Analisis elemen hingga; Kitosan; Dimensi kavitas; Distribusi stress; Distribusi strain.*

ABSTRACT

Composite resin restorations frequently fail due to secondary caries formation. To address this, the antibacterial potential of chitosan for incorporation into dental composites has been explored. Given the limitations of existing studies—which often lack a focus on biomechanical function, this research used an in silico Finite Element Analysis (FEA) to evaluate the combined effects of chitosan addition and cavity dimension on stress and strain distributions within restorative materials. A 3D model of a human mandibular first molar, derived from micro-CT scanning, was subjected to FEA using varying chitosan concentrations (0%, 0.5%, 1.0%, and 2.0%) and two cavity dimensions (conservative and extensive). Statistical results showed significant differences in stress and strain distributions across the treatment groups. Cavity dimensions significantly influence the distribution of stress and strain. The effect of chitosan addition is secondary. The addition of chitosan in cases of extensive cavities was not strong enough to produce statistically significant changes. The FEA analysis demonstrates a clear influence of cavity geometry on biomechanics: In extensive cavities, the restorative material provides superior structural reinforcement, leading to a stiffer composite unit (high stress, low strain) and limited cusp deformation; while in conservative cavities, the structure exhibits a highly flexible response to loading (low stress, high strain), even with a preserved marginal ridge. The stress concentration in the tooth model was primarily in the cervical area, specifically at the cementoenamel junction (CEJ).

Keywords: *Finite element analysis; Chitosan; Cavity dimension; Stress distribution; Strain distribution.*

INTRODUCTION

Dental caries is one of the most common diseases found worldwide (Guo *et al*., 2023). More than one-third of the world's population lives with untreated dental caries. Dental caries is the most widespread noncommunicable disease and a significant public health problem for populations and governments worldwide. Untreated dental caries in permanent teeth is the most prevalent disease, affecting more than 2 billion people worldwide. The estimated global average prevalence of caries in permanent teeth is 28.70% (World Health Organization, 2022).

Restorative treatment is an intervention for carious lesions that involves the placement of dental restorations. This restorative treatment aims to control caries, eradicate biofilm, and restore tooth shape and function (Machiulskiene *et al*., 2020). According to Sun *et al*. (2025), the primary function of dental restorative materials is to restore normal masticatory function. Effective masticatory function supports patient well-being by facilitating proper food consumption and meeting nutritional demands.

Currently, the demand for treatments that provide good aesthetic results is increasing. Composite resin is a dental restorative material that mimics the color of natural teeth. Currently, composite resin is the primary dental material used for direct dental restorations (Ritter *et al*., 2018).

The use of composite resins in dentistry is increasing, along with patients' growing demand for esthetic factors in dental treatment (Tsujimoto *et al*., 2018). Increasing aesthetic demands, combined with a conservative approach, led to greater use of composite resins in various restorative procedures (El-Banna *et al*., 2019). According to Su *et al*. (2023), over the past 17 years, there has been a growing trend toward composite resin fillings for dental cavities. The increasing use of composite resin is influenced by its advantages.

Composite resin restoration has several advantages, including high esthetics, allowing conservative tooth preparation, low thermal conductivity, universal use, being able to adhere to the tooth structure by micromechanical retention, and can be repaired if damaged (Ritter *et al*., 2018; Tsujimoto *et al*., 2018; Kandil & Sherief, 2021). Composite resin also has good mechanical and physical properties (Riva & Rahman, 2019). The use of appropriate composite resin materials produces restorations with the shape, function, and appearance of the original tooth structure. Properly placed composite resin materials produce highly esthetic and durable restorations. The results of composite resin restoration satisfy patients and dentists (Ritter *et al*., 2018). Although composite resin has many advantages, it also has some disadvantages.

There are several disadvantages to composite resin, including polymerization shrinkage, marginal leakage due to bonding failure between the restoration and the tooth surface, and excessive accumulation of oral biofilm on the restoration surface. These disadvantages lead to the failure of composite resin restorations (Hariharavel *et al*., 2017; Rohani, 2019; Askar *et al*., 2020; Nedeljkovic *et al*., 2020; Azhar *et al*., 2022). Currently, the failure of composite resin restorations is primarily attributed to the development of secondary caries around them (Stenhagen *et al*., 2019; Askar *et al*., 2020; Nedeljkovic *et al*., 2020; German, 2022).

The incidence of secondary caries adjacent to composite resin restorations is twice that of amalgam restorations in patients at high risk of caries (Nedeljkovic *et al*., 2015; Ritter *et al*., 2018). Composite resin tends to promote greater oral biofilm formation (Ali *et al*., 2015). The formation of oral biofilm on the surface between the tooth and the material is a significant contributor to the development of secondary caries in composite resin restorations (Stenhagen *et al*., 2019). A good composite resin restoration material prevents the formation of oral biofilm.

Composite resin material has no antibacterial properties. Therefore, composite resin enables the growth of cariogenic bacteria on its surface (Nedeljkovic *et al*., 2015). Biofilm formation triggers secondary caries (Ali *et al*., 2015), which is associated with the lack of antibacterial properties in composite resins (Nedeljkovic *et al*., 2015). Composite resin is more easily adhered to by bacteria than other dental restoration materials.

Various studies have examined incorporating antibacterial agents into resin components to inactivate bacteria and reduce the accumulation of oral biofilms, thereby preventing the development of secondary caries (Sevinç & Hanley, 2010). Chitosan is a natural polysaccharide derived from chitin. Chitosan is considered non-toxic, biocompatible, and biodegradable, and has antibacterial properties (Deb *et al*., 2021). Chitosan is a biomaterial that continues to be developed due to its numerous benefits and proven safety for human use (Merchantara *et al*., 2022). Chitosan has good potential as an antibacterial agent for composite resins (Stenhagen *et al*., 2019).

According to Stenhagen *et al*. (2019), the amount of chitosan required to achieve the composite resin's antibacterial response compromises its mechanical properties. The greater the concentration of chitosan added to the composite resin, the lower its hardness and flexural strength (Stenhagen *et al*., 2019). On the other hand, Kim & Shin (2013) and Tanaka *et al*. (2020) stated that the addition of 1-2% chitosan to composite resin does not reduce the mechanical properties of composite resin. Although chitosan has excellent potential as an antibacterial agent in composite resin, the effect of its addition on mechanical strength remains controversial.

Chitosan has good potential as an antibacterial agent for incorporation into composite resin. These materials need to be investigated for their antibacterial and mechanical properties; however, existing studies have limitations, namely that they have not been carried out on teeth that function mechanically in the oral cavity.

Along with technological developments, computational technology has emerged to overcome these problems and can be adapted across various fields, including the biomedical field. Biomedical research presents specific challenges, as current research can be costly and ethically questionable when conducted on patients. Virtual models and simulation approaches by Finite Element Analysis (FEA) have become the solution (Magne, 2007).

This study aims to evaluate the effects of chitosan addition and cavity dimensions on the stress and strain distributions in restorative materials using a finite element analysis.

Method

This study has received Ethics Committee Approval from the Research Ethics Commission of the Faculty of Dentistry – Prof. Soedomo Dental Hospital, Universitas Gadjah Mada (No. 40/UN1/KEP/FKG-RSGM/EC/2024).

Construction of 3D finite element models

An intact, extracted human permanent mandibular molar tooth, free of caries, with no cracks or fractures, and exhibiting complete root formation, was used in this study. The mandibular molar was scanned using a micro-CT scanner (Bruker MicroCT SkyScan 1173) to obtain digital data.

Scanning and reconstruction using a micro-CT scanner produced a DICOM dataset. Segmentation was then performed using 3D Slicer software to mask enamel and dentin within the tooth scan file. The segmentation file was saved in *.STL format.

The high-resolution scanning process results in bulky mesh sizes. To enable the object files to be opened with computer-aided design (CAD) and finite element analysis (FEA) software, a mesh reduction step was performed using Meshmixer software (Autodesk, Inc.). The object files were exported in STEP format.

The STEP files were opened in SolidWorks 2022 (Dassault Systèmes - SolidWorks Corporation) to design the fundamental structures of enamel, dentin, the cavity (Class I occlusal cavities with conservative and extensive types – Table 1), restoration, adhesive layer, cortical bone, cancellous bone, and the food bolus. The thickness of the bone model is 1.5 mm for cortical bone and 22 mm for cancellous bone. The pulp and periodontal ligament were not included in this study design.

According to the literature, when simulating stress distribution in the crown area (excluding the root area), the periodontal ligament is often not involved. The periodontal ligament was not involved due to its relatively low stiffness (approximately 68.9 MPa) and thin structure (usually 0.2 mm thick). These factors indicate that the periodontal ligament's influence on peak stress in the crown area is negligible (Apel *et al.*, 2021; Ouldyerou *et al.*, 2023). All model parts are combined and exported as a STEP file for further analysis in ANSYS.

Table 1.
Cavity dimensions used in the study

Class of Cavity Preparations	Cavity Dimensions		References
	Conservative	Extensive	
Class I	Height: 2 mm	Height: 3 mm	Tseng *et al.*, 2023
	Diameter: 2 mm	Diameter: 4 mm	

Source: Tseng *et al.*, 2023

Properties of materials

The mechanical properties, particularly the elastic modulus and Poisson's ratio, of enamel, dentin, restoration, adhesive layer, cortical bone, cancellous bone, and food bolus are presented in Table 2. All oral tissues and materials in this study were assumed to be linearly elastic, homogeneous, and isotropic (Ouldyerou *et al.*, 2023).

Table 2.
Mechanical properties of the tooth and composite resin that used in the study

Material	Elastic modulus (GPa)	Poisson's ratio	References
Enamel	84.1	0.33	Sun *et al.*, 2021; Babaei *et al.*, 2022
Dentin	18.6	0.31	Sun *et al.*, 2021; Babaei *et al.*, 2022
Cortical bone	13.7	0.30	Nikam & Milani, 2022
Cancellous bone	1.37	0.30	Nikam & Milani, 2022
Food bolus	3.41 ($x10^{-3}$)	0.10	Ausiello *et al.*, 2017
Adhesive layer	1.0	0.30	Ab Ghani *et al.*, 2023
Composite resin (0% chitosan)	5.3	0.30	Brandão *et al.*, 2018; Yazdani *et al.*, 2022
Composite resin + 0.5% chitosan	5.50	0.30	Tanaka *et al.*, 2020
Composite resin + 1% chitosan	4.40	0.30	Tanaka *et al.*, 2020

Material	Elastic modulus (GPa)	Poisson's ratio	References
Composite resin + 2% chitosan	4.91	0.30	Kim & Shin, 2013

Source: Kim & Shin, 2013; Ausiello *et al*., 2017; Brandão *et al*., 2018; Tanaka *et al*., 2020; Sun *et al*., 2021; Babaei *et al*., 2022; Nikam & Milani, 2022; Yazdani *et al*., 2022; Ab Ghani *et al*., 2023

Mesh, loading, and boundary conditions

The models were imported into ANSYS 2024 (ANSYS, Inc.). All interfaces were considered perfectly bonded. The lower surface of the bone was fully constrained (Ouldyerou *et al*., 2023). A static uniformly distributed occlusal load of 565 N was applied to the occlusal surface of the mandibular molar crown, simulating the average bite force for a molar tooth (Kaladevi & Balasubramaniam, 2020).

A grid independence test (or mesh convergence) was conducted to ensure that the mesh size does not affect the results (Ouldyerou *et al*., 2023). This study uses a 0.3 mm element mesh size.

The subjects were divided into eight groups (Table 3). Three-dimensional FEA simulations were performed for two parameters: chitosan concentrations in the composite resin (0%, 0.5%, 1.0%, and 2.0%) and cavity dimensions (conservative and extensive cavity types) to determine stress and strain distributions. There were three repetitions of the simulation. A total of 48 simulations were executed.

Table 3.
Group Division

Groups	Chitosan Concentrations in Composite Resin	Cavity Dimensions
1	0%	Conservative
2	0.5%	
3	1.0%	
4	2.0%	
5	0%	Extensive
6	0.5%	
7	1.0%	
8	2.0%	

Source: Author's analysis (2025)

RESULTS AND DISCUSSION

Figures 1 and 2 show the results of the FEA simulation for stress and strain distributions. The data obtained are not normally distributed; therefore, nonparametric tests were performed using the Kruskal-Wallis test (Table 4) and the Mann-Whitney test (Table 5).

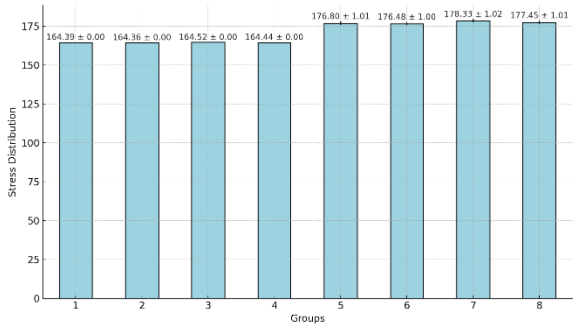

Figure 1.
Average von Mises for stress distributions (in MPa)
Source: Author's analysis (2025)

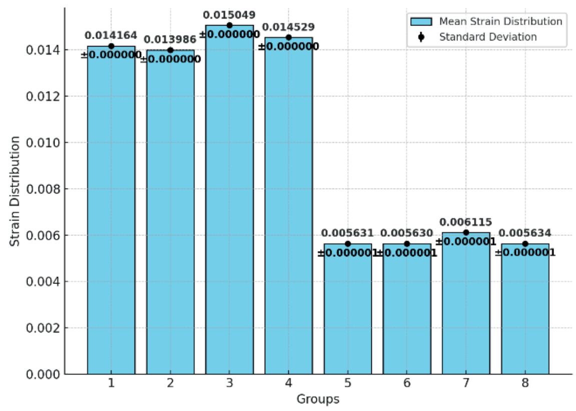

Figure 2.
Average strain distributions (in mm/mm)
Source: Author's analysis (2025)

Table 4.
The results of the Kruskal-Wallis test on the effect of combining antibacterial concentration and cavity dimensions on the stress and strain distribution

Independent Variable	*p*
Stress Distribution	0.003*
Strain Distribution	0.002*

*(p<0.05) = significant difference
Source: Author's analysis (2025)

Table 5.
The results of the Mann-Whitney test demonstrate the effect of combining antibacterial concentration and cavity dimensions on the stress and strain distribution

Group Pairs		p	
		Stress Distribution	Strain Distribution
CH0%, Conservative	CH0.5%, Conservative	0,025*	0,025*
	CH1.0%, Conservative	0,025*	0,025*
	CH2.0%, Conservative	0,025*	0,025*
	CH0%, Extensive	0,034*	0,034*
	CH0.5%, Extensive	0,034*	0,034*
	CH1.0%, Extensive	0,034*	0,034*
	CH2.0%, Extensive	0,034*	0,034*
CH0.5%, Conservative	CH1.0%, Conservative	0,025*	0,025*
	CH2.0%, Conservative	0,025*	0,025*
	CH0%, Extensive	0,034*	0,034*
	CH0.5%, Extensive	0,034*	0,034*
	CH1.0%, Extensive	0,034*	0,034*
	CH2.0%, Extensive	0,034*	0,034*
CH1.0%, Conservative	CH2.0%, Conservative	0,025*	0,025*
	CH0%, Extensive	0,034*	0,034*
	CH0.5%, Extensive	0,034*	0,034*
	CH1.0%, Extensive	0,034*	0,034*
	CH2.0%, Extensive	0,034*	0,034*
CH2.0%, Conservative	CH0%, Extensive	0,034*	0,034*
	CH0.5%, Extensive	0,034*	0,034*
	CH1.0%, Extensive	0,034*	0,034*
	CH2.0%, Extensive	0,034*	0,034*
CH0%, Extensive	CH0.5%, Extensive	0,261	0,261
	CH1.0%, Extensive	0,261	0,043*
	CH2.0%, Extensive	0,261	0,043*
CH0.5%, Extensive	CH1.0%, Extensive	0,043*	0,043*
	CH2.0%, Extensive	0,261	0,043*
CH1.0%, Extensive	CH2.0%, Extensive	0,261	0,043*

*(p<0.05) = significant difference
Source: Author's analysis (2025)

The development of restorative materials containing antibacterial agents is an alternative to reduce the progression of caries lesions (Kikuchi *et al*., 2022). Composite resin is one of the most popular restorative materials for aesthetic dental treatments (Scotti *et al*., 2014). The mechanical properties of restorative materials play a crucial role in determining which materials can mimic the properties of tooth tissue (dentin and/or enamel). The more closely a material matches the properties of teeth, the more uniformly the restorative material can distribute stress and strain across the interface area. The more uniform the distribution of stress and strain, the more durable a restoration will be in the oral cavity (Száva *et al*., 2023).

Stresses occurring in restorative materials and within the oral environment are challenging to visualize in clinical settings. Finite element analysis (FEA) can simulate clinical conditions and allow researchers to evaluate the stresses occurring in restored teeth (Guler, 2022). This study aimed to evaluate the effect of adding an antibacterial agent to composite resin restorations on the stress and strain distribution of restorative materials using an in-silico method.

Finite element analysis is a modern technique that uses numerical methods to analyze stress and solve mechanical problems. This makes the finite element method a valuable tool for contemporary research on the mechanical properties of teeth and restorations in the oral cavity. Finite element analysis provides precise insight into the complex mechanical behavior of restored teeth, where the restored tooth is affected by stress fields that are difficult to assess *in vitro*. Therefore, the FEA is suitable for examining the structural behavior of teeth (Prabhakar & Musani, 2010).

The use of FEA can provide answers to problems in restorative dentistry. FEA results can be practical, applicable, and clinically significant. The results of this FEA can serve as a reference and provide direction for experimental and clinical research. The finite element analysis has significant advantages because it can be applied to solid objects with irregular geometries and heterogeneous material properties (Prabhakar & Musani, 2010). Finite element analysis is very useful in dentistry because it can easily model the complex geometry of teeth and their supporting structures, as well as the large variations in physical properties (Jung *et al*., 2009).

The Kruskal-Wallis test results (Table 4) indicate that the combination of antibacterial concentration and cavity dimensions has a significant effect on the distribution of stress and strain ($p < 0.05$). This significant difference indicates an interaction between antibacterial concentration and cavity dimensions that affects the distribution of stress and strain.

The interaction between these variables can cause effects that are not visible when tested separately. In this study, the Kruskal-Wallis test can capture differences arising from this interaction. When two influencing variables are combined, several new categories are created that combine variations in both variables. The effect of this combination may be more pronounced in the distribution of stress and strain than the effect of each factor separately. The effect of the interaction between antibacterial concentration and cavity dimensions can be further assessed using the Mann-Whitney post hoc test (Table 5).

The most significant variable in this study was cavity dimension. Table 5 shows that nearly all comparisons between the conservative and extensive groups were significant ($p = 0.034$). This indicates that changing cavity dimensions from conservative to extensive has a significant, statistically detectable impact on stress and strain distribution, regardless of the chitosan concentration used.

Cavity geometry is a dominant biomechanical factor influencing stress concentration and load transfer in teeth. In this study, differences in the dimensions of conservative and extensive cavities were observed, which significantly altered the stress distribution under occlusal loading. In the FEA model, static loading, assuming perfect bonding and no shrinkage, resulted in significant differences driven by the cavity volume factor.

The fundamental difference between conservative and extensive models lies in the amount of healthy tooth structure. The amount of remaining healthy hard dental tissue is directly proportional to the stiffness of the tooth-restoration system (Dimitriu *et al*., 2009).

In FEA simulations, when occlusal loads are applied, there is a discrepancy in stress distribution. The occlusal load and stress are distributed between the restorative material (composite resin) and the remaining tooth structure (enamel and dentin) based on their respective elastic moduli (Zheng *et al*., 2022; Gönder *et al*., 2023; Mohammadi *et al*., 2025). In extensive cavities, the composite resin material represents a much larger structural component that must absorb and transfer the load. The load is distributed over a larger composite resin volume and a smaller tooth volume. This results in different stress distribution patterns, which are reflected in significant differences in the statistical analysis.

Based on Table 5, no significant differences were observed among the different chitosan concentrations within the extensive cavity dimension group. There were no significant differences in stress distribution when comparing 0% chitosan with other chitosan concentrations (0.5%, 1.0%, or 2.0%) in extensive cavities. This indicates that when cavities are large (extensive), the addition of chitosan at this concentration does not produce statistically measurable changes in stress performance compared to the group without chitosan at all. The results of the large-cavity preparation are the dominant factor, so the effect of chitosan addition can be ignored.

Conversely, in the conservative cavity dimension group, changes in chitosan concentration always produced significant differences. This implies that in smaller cavities, the composite resin material is more sensitive to the addition of chitosan.

This study used occlusal load to simulate the compressive strength experienced by teeth. Compressive strength is defined as the stress at which a material fails under pressure. The relationship between compressive strength and the distribution of stress and strain in the elastic region is mediated by the modulus of elasticity (also known as Young's modulus).

Materials with high compressive strength typically also have a high modulus of elasticity. The higher the modulus of elasticity, the stiffer the material (Chojnacka-Brożek *et al*., 2024). Stiffer materials exhibit lower strain (deformation) at a given stress. Consequently, during chewing, stiffer composite resins deform less. This reduced deformation helps maintain the marginal integrity of the restoration and prevents microcrack formation at its edges. This, in turn, helps the restoration maintain its shape and integrity when functioning in the oral cavity (Damanik *et al*., 2025).

This study showed that stress distribution values were lower than the compressive strengths of enamel, dentin, and composite resin across all experimental groups (Figure 1). The established compressive strength values are 384 MPa for enamel (Ritter *et al*., 2018; Rodrigues *et al*., 2020), 297 MPa for dentin (Ritter *et al*., 2018; Rodrigues *et al*., 2020), and 291.7 MPa for the composite resin (Abuelenain *et al*., 2015). According to Wu *et al*. (2024), if the stress generated from the simulation results during occlusal loading does not exceed the compressive strength of the natural tooth structure and the composite resin, the probability of fracture under normal occlusal forces is low.

According to Ravandi *et al*. (2024), the addition of 0.5% chitosan can increase the compressive strength of composite resin, while the addition of 1% chitosan can decrease the compressive strength of composite resin. The higher the concentration of chitosan added to the composite resin, the greater its weakening effect on the composite resin's mechanical strength. This can be caused by agglomeration when mixing chitosan into the composite resin. When chitosan agglomerates in the composite resin, it creates weak areas and reduces its surface hardness and compressive strength. Agglomeration can cause stress concentration points. This concentrated stress can cause the composite resin to deform or fail under compressive loads (Ravandi *et al*., 2024). Clinically, deformation can increase the risk of microleakage (Chojnacka-Brożek *et al*., 2024).

Fundamentally, the addition of chitosan tends to weaken the composite resin because it does not bond to its polymer matrix (Shah & Stansbury, 2014). Furthermore, chitosan has poor mechanical properties (Kikuchi *et al*., 2022). Chitosan can be incorporated into the composite resin by crosslinking it with the resin. In this study, based on reference data from Tanaka *et al*. (2020), a crosslinking stage was included in the *in vitro* test by adding 0.5% and 1.0% chitosan to the composite resin.

Incorporating chitosan into the composite resin without crosslinking has been shown to increase the potential for particle aggregation/agglomeration. Increased particle aggregation can lead to increasingly uneven particle dispersion within the polymer matrix, thereby reducing the material's mechanical properties (Kikuchi *et al*., 2022). In this study, this is likely to occur with the addition of chitosan at higher concentrations (2%).

On the other hand, the absence of crosslinking results in a higher concentration of free amine groups compared to crosslinked mixtures. As a macromolecule, chitosan possesses amine groups that can form hydrogen bonds with the hydroxyl groups of the composite resin's polymer matrix. These hydrogen bonds become trapped within the polymer network and are difficult for the material to remove.

The formation of more hydrogen bonds can increase the material's strength, particularly at low chitosan concentrations (Kikuchi *et al*., 2022). However, because the trapped hydrogen bonds are difficult to remove from the composite resin, their contribution is insufficient to affect its flexural strength or elastic modulus significantly (Kikuchi *et al*., 2022). This outcome is closely related to the composite resin's inorganic filler content, which exhibits a strong correlation with its elastic modulus (Randolph *et al*., 2016).

The effect of chitosan addition on the mechanical properties of composite resins, such as elastic modulus and compressive strength, is highly dependent on the concentration and molecular form of chitosan (e.g., nanoparticles, powder). At low concentrations, chitosan particles (especially in nanoparticle form) can be well integrated into the resin matrix, thereby improving the composite's overall structure. This may not interfere with compressive strength and can even increase it (Stenhagen *et al*., 2019).

At higher concentrations, chitosan, as a polymer, is generally softer than inorganic filler materials. This can interfere with the polymerization of the resin matrix and disrupt the important bond between the resin matrix and the inorganic filler particles. This interference makes the composite resin material weaker and less rigid (Dobrzyński *et al*., 2025).

Stress concentration is often caused by sharp corners or geometric discontinuities, as shown in Figures 3 and 4. These two factors become dominant when shrinkage and polymerization stress are not included in FEA simulations.

In this study, the stress concentration was primarily observed at the junction between enamel and dentin in the cervical area. Stress concentration in the cervical area of the tooth was observed in both conservative (Figure 3) and extensive (Figure 4) cavity types. The primary cause of the extreme stress spike is the abrupt change in geometry in the cervical area. This geometric change acts as a stress riser or notch. Although the internal line angle was rounded in this study, the natural anatomy of the tooth in the cervical area involves a cementoenamel junction (CEJ) where the enamel abruptly stops, exposing the underlying dentin structure. The CEJ is the junction between two tooth structures with different properties: the more rigid and brittle enamel and the more pliable and flexible dentin.

The surface of the 3D tooth model in this study shows a sharp edge at the enamel-to-dentin transition at the CEJ. Finite element analysis software will automatically treat this sharp edge as an extreme stress concentration. Stress will naturally concentrate at any point of geometric discontinuity or sharp angle in the load path. According to Vianna *et al*. (2018), the presence of sharp tooth structures increases stress concentration in that area.

The thin enamel walls and underlying dentin flex when an occlusal load is applied. This flexion is most significant in the cervical region. Furthermore, stress is highly concentrated at the DEJ, the interface between the highly flexible dentin and the rigid enamel/restoration complex. This concentration often manifests as a surge in tensile stress, which can pull the materials apart (Sender & Strait, 2023).

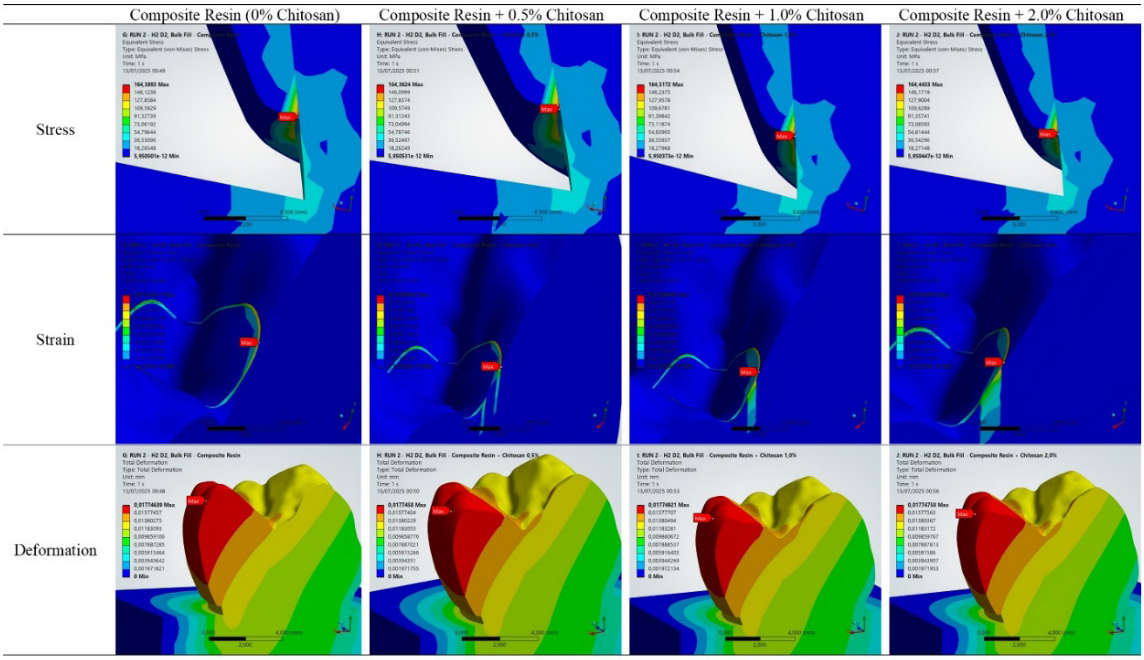

Figure 3.
Finite element analysis simulation results for conservative cavity types
Source: Author's analysis (2025)

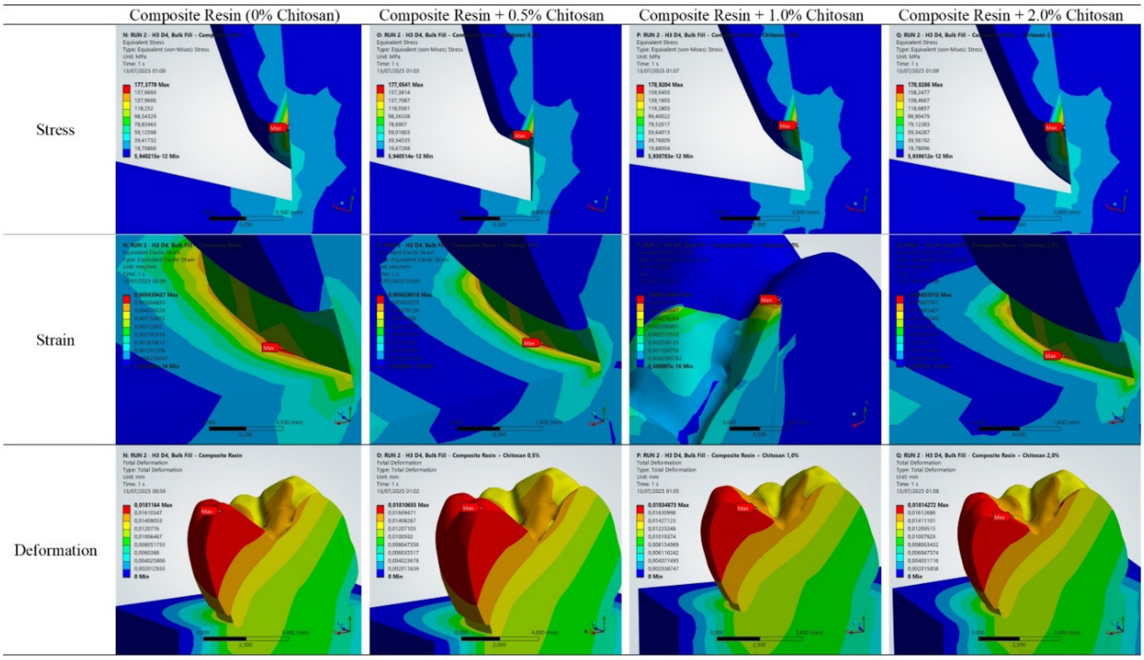

Figure 4.
Finite element analysis simulation results for extensive cavity types
Source: Author's analysis (2025)

Based on research conducted by Sender & Strait (2023), enamel flexure located below the cusp tip subjected to bite force can generate tensile stress at the dentinoenamel junction (DEJ). The presence of tensile stress at the DEJ below the loaded cusp tip then results in lateral expansion of the dentin, which subsequently generates tensile stress at the cervical margin of the tooth (Sender & Strait, 2023). This mechanism allows stress concentration to occur in the cervical area of the tooth below the same cusp (the lingual cusp). These concentration points are commonly known precursors to the occurrence of abfraction lesions and marginal damage in the oral cavity.

Regarding the strain distribution area in a conservative Class I cavity (Figures 3 and 4), most of the supporting dentin is preserved, and the buccal cusps (functional cusps) remain rigid. Under vertical occlusal loads, these rigid buccal cusps resist deformation. As a result, strain is not concentrated at the cavity floor, but rather at the buccal margin of the restoration. Clinically, strain in this location reflects the potential for bond failure or enamel margin fracture due to movement of the restorative material against the rigid enamel walls.

In extensive cavities, the large volume loss of dentin makes the entire crown highly pliable. When a load is applied to the functional (buccal) cusp, the thin remaining dentin fails to support the load, and strain is consequently transmitted and concentrated in the cervical or root area. The concentration of strain in the cervical dentin (beneath the non-functional, lingual cusp) indicates the potential for root or cervical fracture, which is considered the most severe failure in dental restorations.

Strain on the teeth can be seen as cuspal deflection. Cuspal deflection is a common mechanical reaction in teeth restored with composite resin. Several factors influence cuspal deflection in composite resin restorations, including polymerization shrinkage stress, cavity size and design, and occlusal loading (Jlekh & Abdul-Ameer, 2018).

This study assumed no curing stress, so polymerization shrinkage was not simulated. In this study, the polymerization process was assumed to occur without any shrinkage stress. By conducting FEA studies of Class I cavities with the assumption of no curing stress, the impact of mismatched mechanical properties between the tooth and the restorative material can be better analyzed without the influence of polymerization shrinkage stress. This simulation will eliminate the impact of loading stress by accounting for confounding variables such as shrinkage. The absence of shrinkage variables will allow a clearer understanding of stress distribution patterns induced by external forces, such as occlusal loads (Tuncdemir *et al*., 2021; Guler, 2022; Ouldyerou *et al*., 2023; Karaköy *et al*., 2024). In this study, polymerization shrinkage, the primary driver of deflection, was not simulated. Therefore, the measured stress and strain are entirely attributable to the simulated masticatory load (occlusal load), the material property distribution, and the cavity dimensions.

Based on the data for average stress distribution (Figure 1) and average strain distribution (Figure 2), the FEA simulations show that extensive cavities (Groups 5-8) yield a stiffer composite structure (tooth and restoration) under occlusal loading (characterized by high stress, low strain). Conversely, conservative cavities (Groups 1-4) yield a more flexible structure (characterized by low stress, high strain). Assuming a perfect bond and no polymerization shrinkage, these findings imply that the restorative material used in extensive cavities acts as superior reinforcement that effectively limits cusp deformation (strain). In contrast, the material used in conservative cavities produces a highly flexible response to loading, even though the marginal ridge is preserved.

Finite element analysis (FEA) is a simplification of reality. The 3-dimensional (3D) tooth model used in this study may not accurately capture the mechanical effects of chitosan. Most FEA studies in dentistry assume that composite resin materials are homogeneous and isotropic (i.e., their properties are uniform across the surface and in all directions). This assumption effectively smooths out any local and microscopic variations, such as poor chitosan dispersion or interference at the matrix-filler interface. However, under actual clinical conditions, these factors will affect the stress distribution in the original material (Fidancioğlu *et al*., 2025).

CONCLUSION

Based on this discussion, some points can be concluded. Cavity dimensions play a pivotal role in determining stress and strain distribution within the restored tooth structure, whereas the influence of chitosan addition is secondary. Finite Element Analysis (FEA) findings indicate that cavity geometry exerts a direct and substantial effect on biomechanical behavior. In extensive cavities, restorative material provides superior structural reinforcement, creating a stiffer composite unit characterized by high stress and low strain, effectively limiting cusp deformation. Conversely, in conservative cavities, the tooth structure displays greater flexibility under loading conditions, resulting in low stress and high strain despite the preservation of the marginal ridge.

However, adding chitosan to extensive cavities did not yield statistically significant biomechanical changes, suggesting that its reinforcing capacity is insufficient under high-stress conditions. Across all simulations, stress concentration was predominantly observed in the cervical area, particularly at the cementoenamel junction (CEJ), a critical site of stress accumulation. This pattern highlights the importance of cavity design in maintaining structural integrity. It underscores that chitosan's contribution remains limited compared to the dominant influence of cavity geometry on the overall biomechanical performance of the restored tooth.

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