

# Finite element analysis of stress distribution in porcelain fused to metal and dual - ceramic polymer crown on mandibular molars with varied tooth preparation designs opposing maxillary molars

Dr. Suvajit Adak<sup>1</sup>, Dr. Arunachalam Sudheer<sup>2</sup>, Dr. Piyali Sarkar<sup>3</sup>, Dr. MD Akmal ariff<sup>4</sup>, Dr. Abhilash<sup>5</sup>, Dr. Samreen Fatma<sup>6</sup>

<sup>1</sup>P.G.T. Final Year Department of Prosthodontics and Crown & Bridge Mithila Minority Dental College And Hospital  
Email ID : Suvajitadak999@gmail.com

<sup>2</sup>Principal And HOD Department of Prosthodontics and Crown & Bridge Mithila Minority Dental College And Hospital  
Email ID : Sudheerdr666@gmail.com

<sup>3</sup>Assistant Professor Department of Prosthodontics and Crown & Bridge Mithila Minority Dental College And Hospital  
Email ID : dr.piyalisarkar1989@gmail.com

<sup>4</sup>P.G.T. Final Year Department of Prosthodontics and Crown & Bridge Mithila Minority Dental College And Hospital  
Email ID : ariffimplant@gmail.com

<sup>5</sup>P.G.T. Final Year Department of Prosthodontics and Crown & Bridge Mithila Minority Dental College And Hospital  
Email ID : Abhilashanand3@gmail.com

<sup>6</sup>Associate Professor Department of Oral Pathology & Microbiology Mithila Minority Dental College And Hospital  
Email ID : Samreenfazal23@gmail.com

## Corresponding author

Dr. Suvajit Adak

P.G.T. Final Year

Department of Prosthodontics and Crown & Bridge Mithila Minority Dental College And Hospital

Email ID : Suvajitadak999@gmail.com

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## ABSTRACT

**Aim** - To compare and evaluate the stress distribution in porcelain fused to metal and dual ceramic polymer crowns on mandibular molar with anatomical and non-anatomical tooth preparation opposing maxillary molars by using Finite Element Analysis.

**Material and method** - Finite element analysis was performed using ANSYS 18.1 on a three-dimensional mandibular first molar model. Four crown designs were evaluated: PFM and dual-ceramic polymer crowns with anatomical and non-anatomical preparations. A static load of 400 N was applied, distributed as 200 N on the buccal cusp tip and 200 N along the central developmental groove. The cement layer was neglected, and enamel was assumed to be completely removed. Materials were assumed homogeneous, isotropic, and linearly elastic, with properties derived from literature.

**Result** - Finite element analysis under 400 N load showed higher stress concentration in PFM crowns at cervical margins and occlusal contacts. Dual-ceramic polymer crowns exhibited more uniform stress distribution with lower peak values. Non-anatomical preparations increased stress at axial walls and root apex, while polymer crowns demonstrated superior biomechanical performance.

**Conclusion** - PFM crowns showed higher stress concentration at occlusal and cusp regions. Dual-ceramic polymer crowns distributed stress more evenly but transmitted some stress to underlying dentin. Anatomic tooth preparation reduced stress concentration and provided better biomechanical performance compared to non-anatomical preparation.

**Keywords:** 3D-Finite Element Analysis (FEA), Porcelain-fused-to-metal (PFM) crown, Dual-ceramic polymer crown, Stress distribution pattern

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## INTRODUCTION

Metal-ceramic restorations have long been the gold standard in prosthetic dentistry due to their proven long-term success. However, increasing demand for improved aesthetics has led to the development of tooth-colored

materials, although PFM crowns remain widely used with well-established clinical reliability.<sup>1,2</sup>

PFM restorations offer excellent marginal adaptation, accuracy, and predictable long-term outcomes, contributing to their widespread use with minimal adverse effects.

However, their esthetic limitations include a greyish discoloration from the metal substructure and reduced translucency, especially in anterior regions.<sup>3,4</sup> The metal framework restricts light transmission, affecting natural appearance. Additionally, the increasing cost of precious metals poses an economic disadvantage, encouraging the development and use of alternative tooth-colored restorative materials.<sup>5,6,7</sup>

All-ceramic crowns have gained popularity due to their superior esthetics, biocompatibility, and favorable gingival response, with marginal accuracy comparable to metal-based restorations. Advances in dental ceramics, including reinforced glass ceramics, zirconia, alumina, leucite, and lithium disilicate, have improved strength and durability. Among these, zirconia, a polycrystalline ceramic, offers excellent mechanical properties, low corrosion, low thermal conductivity, good radiographic contrast, and superior biocompatibility, making it highly promising.<sup>8,9</sup>

Zirconia exists in tetragonal, cubic, and monoclinic forms and is stabilized with oxides like yttria (Y-TZP). It offers high strength and fracture toughness. Lava zirconia is widely used. Hybrid ceramics like Vita Enamic combine ceramic strength with composite resilience, reducing brittleness and improving CAD/CAM fabrication efficiency.<sup>10,11</sup>

PFM restorations allow selective tooth reduction, with less preparation in metal-covered areas. In contrast, zirconia requires precise, uniform preparation. Anterior teeth need 1–1.5 mm reduction, while posterior teeth require 1.5 mm occlusal and 1 mm axial reduction with proper taper for strength and esthetics.<sup>2,10</sup>

Numerous studies have used finite element analysis (FEA) to examine the failure behaviour of specific restorative materials and the pattern of stress distribution.<sup>12,13</sup>

Finite element analysis (FEA) is a valuable tool for studying biomechanics of complex structures. It simulates stress, force direction, and magnitude by dividing structures into elements and nodes. FEA is non-invasive, repeatable, and accurate. It involves creating models, assigning material properties, and applying loads and boundary conditions using specialized software.<sup>14,15</sup>

The study aimed to evaluate the stress distribution in between PFM and All-Ceramic crown with different tooth preparations on mandibular first molar opposing maxillary first molar.

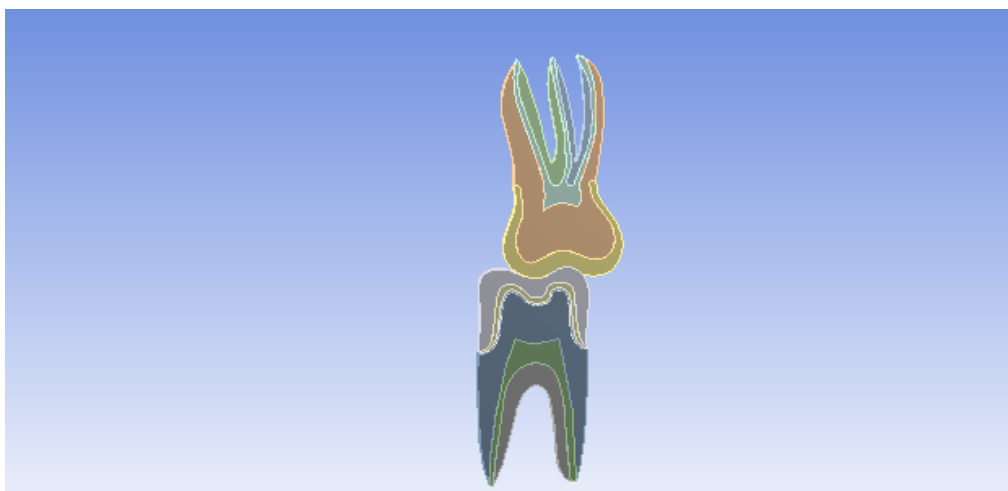
## MATERIALS AND METHOD

The FEA was conducted on a personal computer (CPU unit: Meshing Hypermesh v11, Memory: 8GB, Disc Drive: 500 GB, Display: Compatible Graphic Color Display, Graphics Adaptor: 4 GB) with a structural analysis program (Ansys v 18.1 for analysis and Solid edge v19 for Modeling) and outputs were transferred to a program to display stress values.

Anatomical models of the mandibular first molar was created using a programmed geometric approach described by Nelson.<sup>16,17</sup>

Based on the established geometry, finite element models of the mandibular first molar were developed. Each model was discretized, assigned material properties, boundary and loading conditions, and analyzed using post-processing software to evaluate stress distribution patterns.<sup>18</sup>

The model (Model 1) represents PFM crown fabricated on a tooth prepared using an anatomic occlusal reduction design, in which the reduction followed the natural cusp inclinations and occlusal anatomy of the mandibular first molar (**Figure 1**).



**Figure 1: CAD model (PFM crown with anatomic tooth preparation) (Model 1)**

(Model 2) represented a PFM crown on a tooth prepared with a nonanatomic occlusal reduction (**Figure 2**), featuring a flat surface without cusp replication. Two additional models used dual-ceramic polymer crowns: (Model 3) with anatomic design and (Model 4) with non-anatomic design (**Figure 3 and Figure 4**).

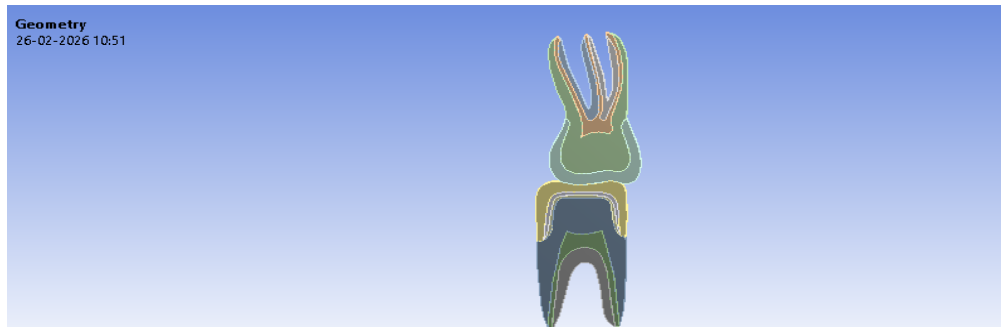


Figure 2: CAD model (PFM crown with non-anatomic tooth preparation) (Model 2)

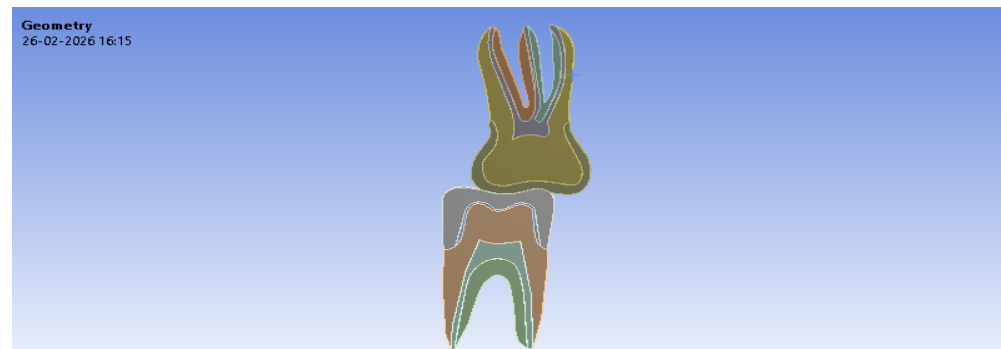


Figure 3: CAD model (Dual-ceramic polymer crown with anatomic tooth preparation) (Model 3)

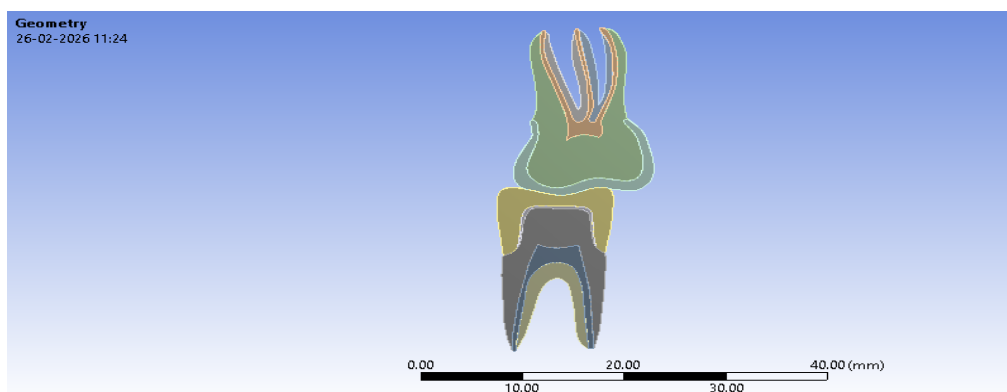


Figure 4: CAD model (Dual-ceramic polymer crown with non-anatomic tooth preparation) (model 4)

Crown geometry was designed with a 0.3 mm core, porcelain thickness of 1.2 mm over functional cusps and 1.7 mm over non-functional cusps (Model 3 and Model 4), a 1 mm shoulder finish line, and 6° total occlusal convergence. PFM crowns had 0.5 mm metal and 1.2 mm porcelain thickness (Model 1 and Model 2). Each model was subdivided into finite elements composed of nodes defined by X- and Y-coordinates for numerical analysis.<sup>19,20</sup>

To convert the continuous anatomical structure into a format suitable for computational analysis, the crown and tooth models were discretized into a finite number of smaller components through a process known as meshing. In this study, each model was divided into 126702 tetrahedral elements inter-connected at 297042 nodes (Figure 5,6,7 and 8). These elements and nodes collectively formed a structured mesh, enabling the software to accurately calculate stress distribution and deformation within the restored tooth complex. A refined mesh improves the precision of the simulation by representing the geometry more accurately.

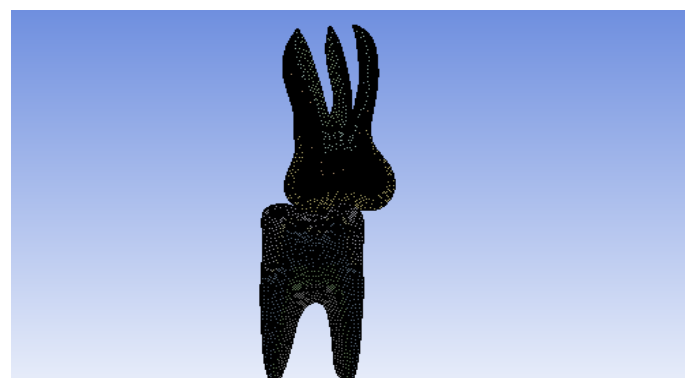
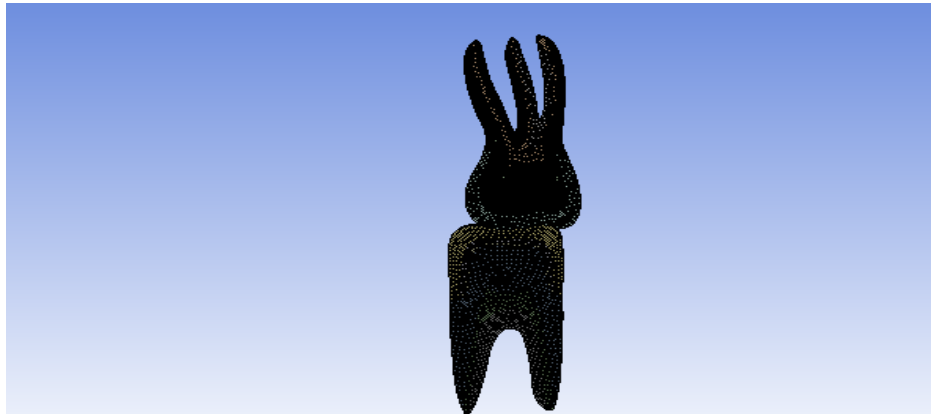
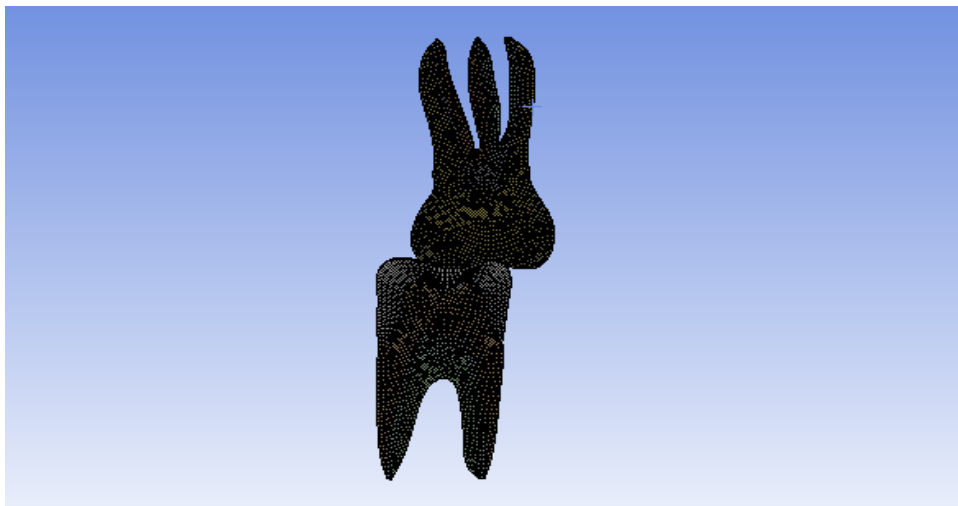


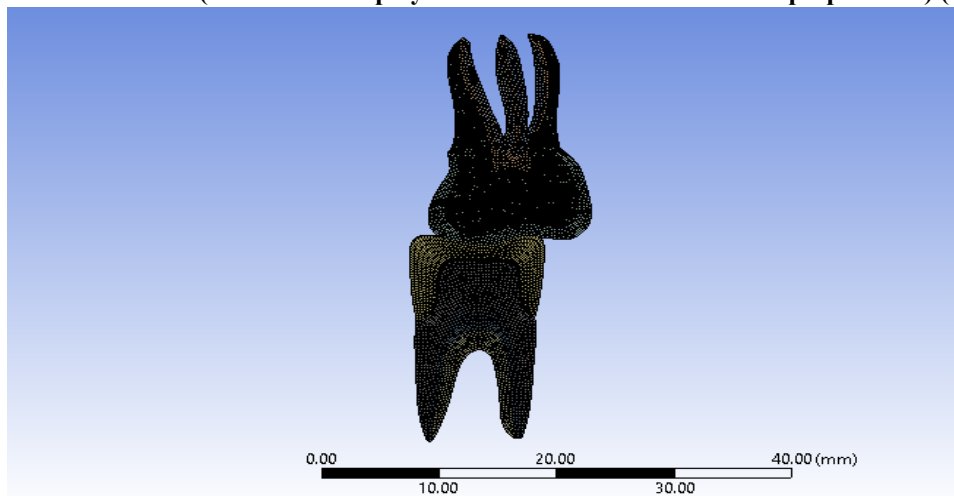
Figure 5: Meshed model (PFM crown with anatomic tooth preparation) (Model 1)



**Figure 6: Meshed model (PFM crown with non- anatomic tooth preparation) (Model 2)**



**Figure 7: Meshed model (Dual- ceramic polymer crown with anatomic tooth preparation) (Model 3)**



**Figure 8: Meshed model (Dual- ceramic polymer crown with non-anatomic tooth preparation) (Model 4)**

To simulate functional occlusal contact, loads were applied at two regions of the model. A 200 N force was placed on the buccal cusp tip at the centric stop, and another 200 N load along the central groove. These forces were distributed over contact areas rather than single nodes, better

replicating physiological mastication. This approach enabled accurate assessment of stress distribution within the crown and its transmission to underlying tooth structures. The mandibular first molar was fixed in position and incorporated in alveolar bone. Standard tooth

preparation principles were applied for the tooth preparation and crown placement on the above mentioned tooth. These loading points represented the areas of primary occlusal contact during normal function. The thickness of the luting cement layer was neglected in the models to simplify the analysis. Additionally, it was also assumed that the enamel tissue is completely removed during tooth preparation, and the prepared tooth structure consisted entirely of dentin. All materials were assumed to be linear elastic, homogenous and isotropic.

The mechanical properties of oral tissues and crown materials, including the modulus of elasticity and Poisson's ratio, were assigned based on values reported in established literature on finite element analysis of dental restorations. The properties of oral tissues and prosthetic materials were considered according to the (Table 1). The values were fed in the ANSYS software for analyzing the stress distribution.

	<b>ELASTIC MODULUS (MPa)</b>	<b>Poisson's ratio (n)</b>	<b>Density (g/cm<sup>3</sup>)</b>
<b>Enamel</b>	83000	0.33	3.00
<b>Dentin</b>	18	0.33	2.12
<b>Pulp</b>	2	0.45	0.22
<b>PFM-crown alloy<sup>a</sup></b>	220000	0.30	8.6
<b>PFM-crown ceramic<sup>a</sup></b>	82800	0.35	2.5
<b>Dual-ceramic polymer crown<sup>b</sup></b>	30000	0.23	2.1
<b>Bone</b>	13.7	0.30	1.3
<b>Periodontal ligament</b>	69	0.45	1.05

<sup>a</sup>Data obtained from BEGO USA

<sup>b</sup>Data obtained from Vita Zahnfabrik

**Table 1: Mechanical properties of oral tissues and prosthetic materials in finite element analysis evaluations**

## RESULTS

Finite element analysis was performed to evaluate stress distribution patterns in four different models of mandibular first molars restored with either porcelain-fused-to-metal (PFM) crowns or dual-ceramic polymer crowns, under anatomic and non-anatomic occlusal preparation designs. The applied loading conditions simulated functional occlusion using two vertical forces of 200 N each, acting on the buccal cusp tip and central developmental groove, totaling 400 N.

### MODEL 1

In Model 1, representing a mandibular first molar restored with a PFM crown and anatomic occlusal preparation, stress distribution was primarily concentrated at the occlusal contact areas and the cervical region. Shear stress analysis in the X–Y plane demonstrated maximum stress concentration at the occlusal interface where force was applied, indicated by warmer color zones (red and yellow). Moderate stress distribution was observed across the coronal dentin and root structure, suggesting effective load transfer. Tensile and compressive stress evaluation revealed maximum stress values of approximately 4123.8 MPa and minimum values of –3949.8 MPa. Tensile stresses were predominantly located at the occlusal surface and outer crown contour, while compressive stresses were concentrated in the cervical and internal dentin regions. Shear stress in the X–Z plane ranged between 804.12 MPa and –801.1 MPa, with peak values again observed at occlusal contact and cervical regions. Probing analysis showed shear stress values on central developmental groove of crown was 61.234 Mpa, on buccal cusp tips it were -32.054 Mpa and 164.57 Mpa. on the tip of remaining dentin 2.4491Mpa and -1.6251 on apex of root it were 14.034 Mpa and -5.0048 Mpa (Figure 9).

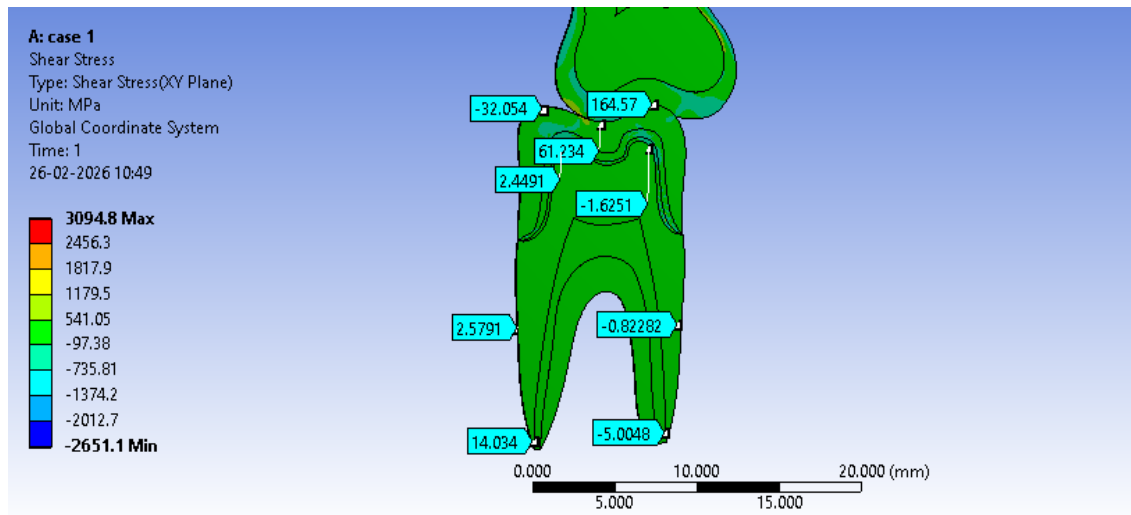


Figure 9: Probing areas (Model 1)

### MODEL 2

Model 2 demonstrated significantly different stress patterns compared to Model 1. The non-anatomic occlusal design resulted in increased stress concentration at the cervical region and along the vertical walls of tooth preparation. Shear stress analysis showed pronounced stress localization at the crown-tooth interface. Tensile and compressive stress values were markedly higher, with a maximum of 13606 MPa and a minimum of -16001 MPa, indicating greater stress accumulation. The stress contour revealed that vertical preparation walls bore a substantial portion of occlusal load, suggesting inefficient stress distribution. Shear stress values in the X-Z plane ranged from 821.42 MPa to -817.44 MPa, with peak stresses located at the interface between the crown and tooth structure.

Probed value on the tooth showed a mix of positive and negative shear stress. Stress value on central developmental groove of crown was 10.193 Mpa, on buccal cusp tips it were -34.931 Mpa and 100.31 Mpa, on the tip of remaining dentin 2.6304 Mpa and -2.5031 on apex of root it were 3.093 Mpa and -1.1873 Mpa (Figure 10).

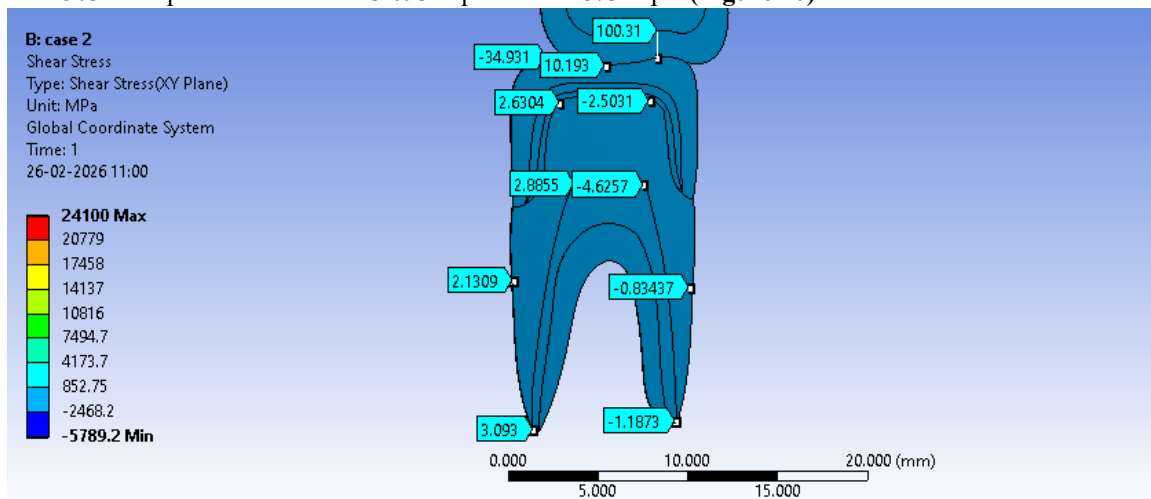


Figure 10: Probing areas (Model 2)

### MODEL 3

Model 3 exhibited improved stress distribution compared to PFM models, particularly in terms of reduced peak stress values. The highest stress concentrations were localized at occlusal contact points, specifically at the buccal cusp tip and central groove, as expected under functional loading. Tensile and compressive stress values ranged from 1898.4 MPa to -2619.8 MPa, significantly lower than those observed in PFM models. Stress distribution appeared more uniform, with moderate stress levels extending across the cervical region and dentin. Shear stress analysis (X-Z plane) showed values between 351.93 MPa and -352 MPa, indicating reduced shear stress magnitude compared to Models 1 and 2.

Stress value on the central developmental groove of crown was 100.05MPa, on buccal cusp tips it were -28.704MPa and 29.603MPa, on tip of remaining dentin 1.4413MPa and -1.5648MPa, on apex of root it were 16.597MPa and -0.8674MPa (Figure 11).

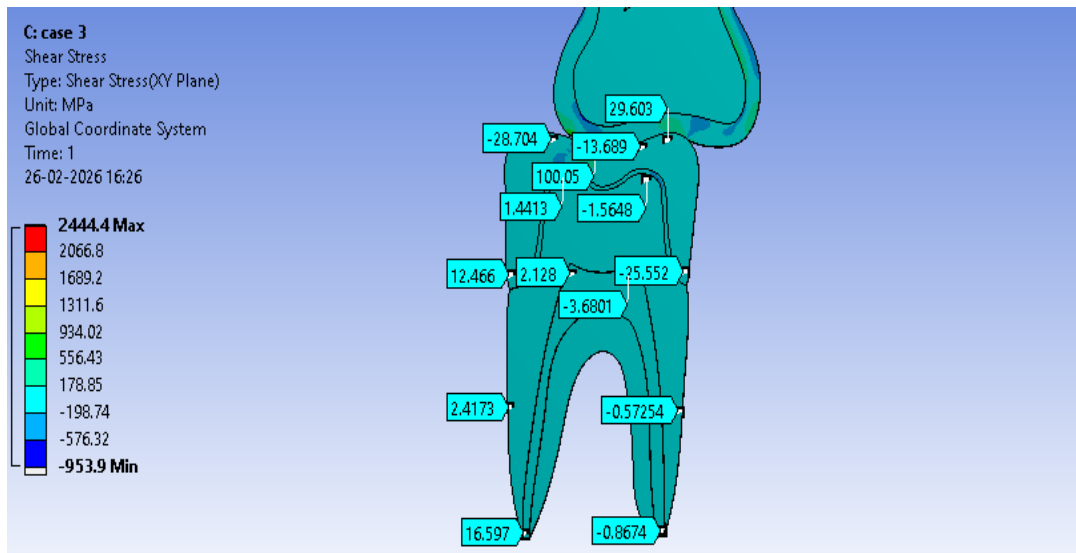


Figure 11: Probing areas (Model 3)

#### MODEL 4

Model 4 presented a distinct stress distribution pattern, with maximum stress concentrations shifting toward the root apex region. Unlike other models, peak shear stress was observed apically rather than at the occlusal or cervical regions. Tensile and compressive stress values ranged from 13240 MPa to  $-15886$  MPa, indicating high stress magnitudes similar to Model 2. Shear stress in the X–Z plane ranged from 429.36 MPa to  $-429.38$  MPa, with peak values concentrated at the root apex. probed value on the tooth showed a mix of positive and negative shear stress. Stress value on central developmental groove of crown was 1.4651Mpa, on buccal cusp tips it were 5.3247Mpa and  $-2.2035$ Mpa, on the tip of remaining dentin 14.09Mpa and  $-18.27$ MPa on apex of root it were 19.004Mpa and  $-3.3223$ Mpa (Figure 12).

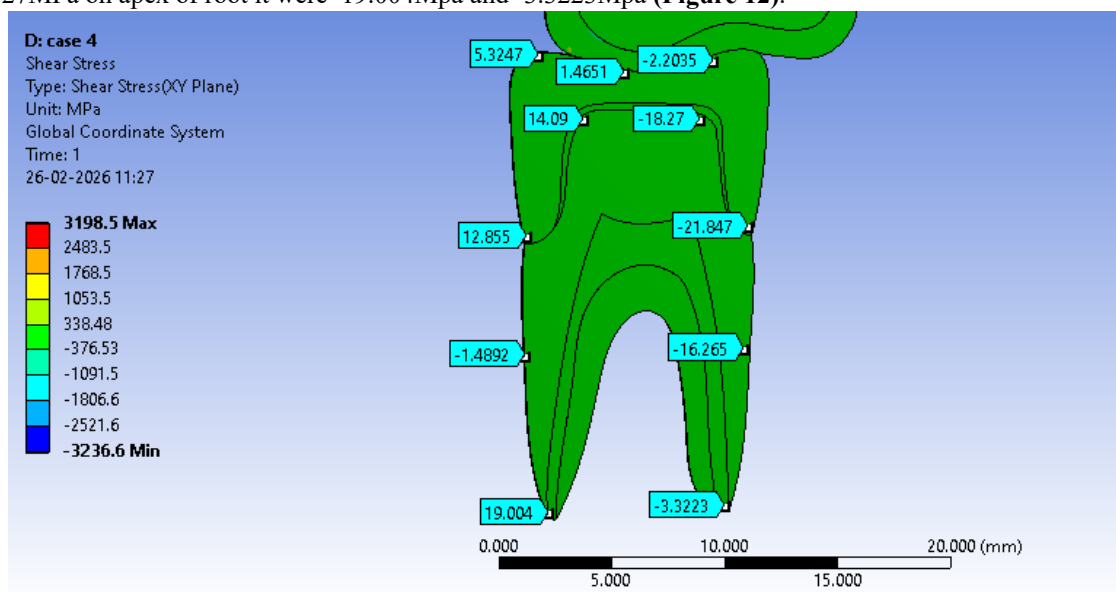


Figure 12: Probing areas (Model 4)

Comparison between Models 1 and 3 (anatomic preparations) demonstrated that dual-ceramic polymer crowns exhibited lower stress magnitudes and more uniform stress distribution than PFM crowns. While both models showed stress concentration at occlusal contact points, Model 3 had significantly reduced peak values, indicating better biomechanical performance (Table 2).

Similarly, comparison between Models 2 and 4 (non-anatomic preparations) revealed that both models experienced higher stress concentrations than their anatomic counterparts. However, Model 4 showed a distinct shift of stress toward the root apex, whereas Model 2 concentrated stress at the cervical interface and preparation walls (Table 3).

<b><u>Probing Areas</u></b>	<b><u>PFM Crown (Anatomic tooth preparation) (MPa) Model 1</u></b>	<b><u>Dual-Ceramic Polymer Crown (Anatomic tooth preparation) (MPa) Model 3</u></b>
<b>Central developmental groove</b>	61.234	100.05
<b>Buccal cusp and crown tip (point 1)</b>	-32.054	-28.704
<b>Buccal cusp and crown tip (point 2)</b>	164.57	29.603
<b>Tip of dentin (point 1)</b>	2.4491	1.4413
<b>Tip of dentin (point 2)</b>	-1.6251	-1.5648
<b>Root apex (point 1)</b>	14.034	16.597
<b>Root apex (point 2)</b>	-5.0048	-0.8674

**Table 2: Shear stress at pinned contact point (Model 1 vs Model 3)**

<u>Probing Areas</u>	<u>PFM Crown (Non-anatomic tooth preparation) (MPa) Model 2</u>	<u>Dual-Ceramic Polymer Crown (Non-anatomic tooth preparation) (MPa) Model 4</u>
Central developmental groove	10.193	1.4651
Buccal cusp and crown tip (point 1)	-34.931	5.3247
Buccal cusp and crown tip (point 2)	100.31	-2.2035
Tip of dentin (point 1)	2.6304	14.09
Tip of dentin (point 2)	-2.5031	-18.27
Root apex (point 1)	3.093	19.004
Root apex (point 2)	-1.1873	-3.3223

**Table 3: Shear stress at pined contact point (Model 2 vs Model 4)**

**STASTICAL ANALYSIS**

As mentioned in Table 2:

**MODEL 1 VS MODEL 3 (Graph 1)**

**Overall stress distribution:**

**PFM Crown:** Mean stress: 29.09 MPa; SD: 62.45 MPa; maximum tensile stress: 164.57 MPa (buccal cusp tip – point 2); maximum compressive stress: –32.05 MPa (buccal cusp tip – point 1); range: 196.62 MPa. High SD indicates wide stress variation with peak tensile stress at the buccal cusp tip.

**Dual-Ceramic Polymer Crown:** Mean stress: 16.65 MPa; SD: 40.53 MPa; maximum tensile stress: 100.05 MPa (central developmental groove); maximum compressive stress: –28.70 MPa (buccal cusp tip – point 1); range: 128.75 MPa. Lower mean and SD indicate more uniform stress distribution.

**Site-Specific Comparison**

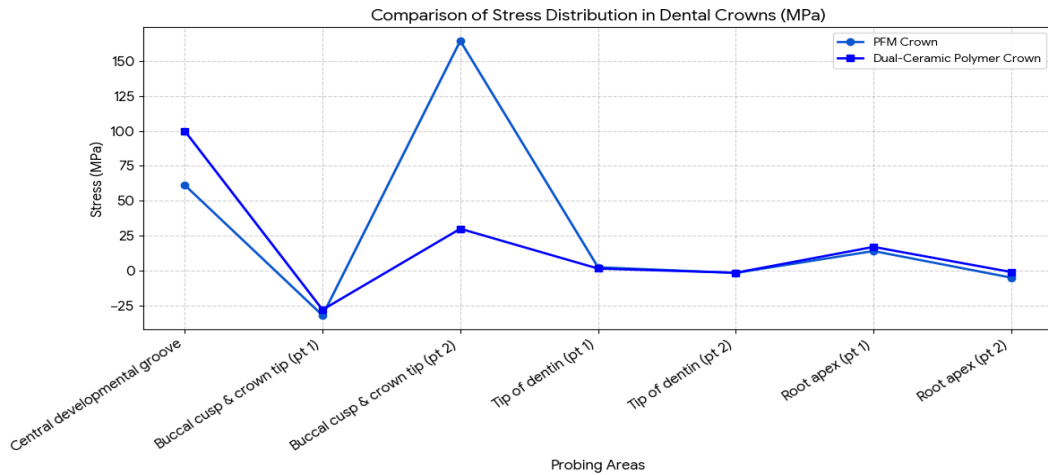
**Central developmental groove:** Higher stress observed in Dual-Ceramic Polymer crown (100.05 MPa) compared to PFM (61.23 MPa).

**Buccal cusp (point 2):** Markedly higher tensile stress in PFM (164.57 MPa) than Dual crown (29.60 MPa).

**Dentin tips:** Both crowns exhibited low stress values, indicating minimal stress transmission to dentin.

**Root apex:** Comparable stresses in both crowns, with slightly higher tensile stress in the Dual crown.

**Interpretation:** The PFM crown demonstrated greater stress variability and higher peak tensile stress, particularly at cusp tips. The Dual-Ceramic Polymer crown showed relatively lower stress concentration and more favorable stress distribution under anatomic tooth preparation.



**Graph 1: Comparison of stress distribution in between PFM and Dual-Ceramic Polymer crown (Anatomic) (Model 1 and Model 3)**

As mentioned in Table 3:

**MODEL 2 VS MODEL 4 (Graph 2)**

**Overall stress distribution:**

**PFM Crown:** Mean stress: 11.09 MPa; maximum tensile stress: 100.31 MPa; maximum compressive stress: -34.93 MPa; range: 135.24 MPa.

**Dual-Ceramic Polymer Crown:** Mean stress: 2.87 MPa; maximum tensile stress: 19.00 MPa; maximum compressive stress: -18.27 MPa; range: 37.27 MPa.

**Site-Specific Comparison**

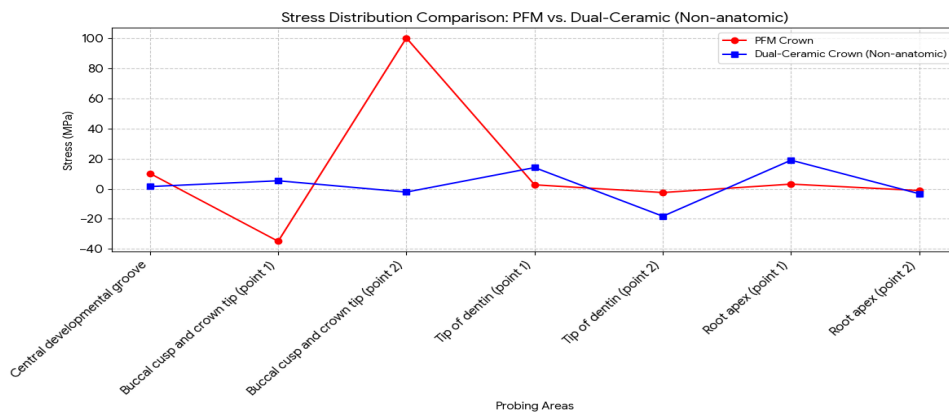
**Central Developmental Groove:** Stress values were low in both groups; however, PFM (10.19 MPa) showed higher tensile stress than the dual-ceramic polymer crown (1.47 MPa).

**Buccal Cusp and Crown Tip:** At point 2, the PFM crown exhibited significantly higher tensile stress (100.31 MPa), whereas the dual-ceramic polymer crown showed minimal compressive stress (-2.20 MPa). At point 1, compressive stress was greater in the PFM crown (-34.93 MPa) compared to the dual-ceramic polymer crown (5.32 MPa tensile).

**Dentin Tips:** The dual-ceramic polymer crown demonstrated higher stress values (14.09 MPa tensile and -18.27 MPa compressive) compared to the PFM crown ( $\pm 2.6$  MPa), indicating relatively greater stress transmission to dentin.

**Root Apex:** Higher tensile stress was observed in the dual-ceramic polymer crown (19.00 MPa) compared to the PFM crown (3.09 MPa), while compressive stresses were mild in both models.

**Interpretation:** Overall, the PFM crown showed greater localized tensile stress concentration at occlusal contact areas under non-anatomic preparation. In contrast, the dual-ceramic polymer crown exhibited lower peak stresses but comparatively increased stress transfer to dentin and root regions, suggesting a difference in stress distribution pattern between the two restorative materials.



**Graph 2: Comparison of stress distribution in between PFM and Dual-Ceramic Polymer crown (Non-Anatomic) (Model 2 and Model 4)**

## DISCUSSION

This finite element analysis compared stress distribution in porcelain-fused-to-metal (PFM) and dual-ceramic polymer crowns on mandibular first molars using anatomic and non-anatomic tooth preparations under 400 N occlusal loading. The models consisted of 126,702 elements and 297,042 nodes, ensuring accurate stress prediction. Standard assumptions of linear elasticity, homogeneity, and isotropy were applied.

In anatomic preparation, the PFM crown (Model 1) showed higher mean stress (29.09 MPa) and variability (SD 62.45 MPa), with peak tensile stress at the buccal cusp tip (164.57 MPa). However, dentin stress remained minimal, indicating effective protection of underlying structures. The dual-ceramic polymer crown (Model 3) demonstrated lower mean stress (16.65 MPa) and more uniform distribution, though higher stress was noted at the central groove (100.05 MPa). Dentin and root stresses were comparable between both materials. In non-anatomic preparation, PFM crown (Model 2) showed reduced mean stress (11.09 MPa) but maintained a wide stress range (135.24 MPa), with continued protection of dentin. The dual-ceramic polymer crown (Model 4) exhibited the lowest mean stress (2.87 MPa) and highly uniform distribution; however, it transmitted greater stress to dentin and root structures.

Comparison revealed that anatomic preparation increased crown stress but improved stress attenuation to deeper tissues for both materials. PFM concentrated stress coronally due to its rigid metal substructure, while the dual-ceramic polymer, with lower elastic modulus, distributed stress more evenly but transferred higher loads apically under non-anatomic preparation.

Clinically, anatomic preparation is preferable for dual-ceramic polymer crowns and beneficial for protecting tooth structure in PFM restorations. High-stress areas, such as cusp tips and central grooves, may represent potential failure sites. Limitations include simplified material assumptions, exclusion of the cement layer, static loading, and limited clinical simulation. Overall, both material and preparation design significantly influence stress distribution, emphasizing the need for material-specific preparation strategies to optimize biomechanical performance and long-term success.

## CONCLUSION

Finite element analysis demonstrated that both crown material and tooth preparation design significantly influence stress distribution in restored mandibular first molars. PFM crowns exhibited higher localized stress concentrations, particularly at cusp tips, but effectively protected underlying dentin due to their rigidity. In contrast, dual-ceramic polymer crowns showed more uniform stress distribution with lower peak stresses, owing to their modulus similarity to dentin. Anatomic preparation designs produced more favorable stress patterns by reducing stress transmission to deeper structures. Overall, dual-ceramic polymer crowns demonstrated superior biomechanical

performance, while PFM crowns provided effective stress shielding of the tooth under occlusal loading conditions

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