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Stress Distribution of CAD CAM indirect PEEK Inlay with Deep Elevated Compromised Distal Cervical Margin in Molars: Finite Element Analysis

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ABSTRACT

Background: Mandibular molars lose hard tissue due to many factors, such as caries, wear, and old restoration replacement. To restore missing tooth structure, the dental material used should be biologically compatible with the surrounding tissues and capable of withstanding the forces of mastication. In addition, there are difficulties in isolating the deep proximal margins from oral fluids to take an accurate impression and cement the indirect restorations. Thus, Finite element analysis (FEA) is adopted to evaluate the influence of stress distribution of elevated cervical margin of deep distal caries using flowable composite with different levels of elevated margins on MOD mandibular molars CAD CAM indirect PEEK inlay.

Methods: Three 3D mandibular left first molar models were prepared according to the level of elevated cervical margin of deep distal caries of (MOD). Stress distribution in FEA was analyzed using the von Mises theory, after applying vertical and oblique forces. Moreover, an oblique force of 600 N was used.

Results: This study shows that oblique forces have resulted in stress values and stress concentrations in dental tissues and restorations higher than those caused by vertical forces in the three models.

Conclusions: We can conclude that badly broken-down molars restored with PEEK CAD CAM indirect inlay and a 2 mm elevated I cervical margin of the deep distal cavity using flowable composite have the lowest stress on the gingival step, compared with a 1 mm elevated cervical margin and a PEEK inlay cervical margin of the deep distal cavity.

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KEYWORDS
indirect PEEK inlay, Stress distribution, elevated cervical margin, compromised cervical margin, CAD CAM indirect PEEK inlay.

1. Introduction

Mandibular molars have hard tissue lose due to many factors, such as caries, wear, and old restoration replacement (1). The dental material used should be biologically compatible with the surrounding tissues and capable of withstanding the forces of mastication. Moreover, restorations can be direct or indirect (2). The inlay\onlay is an intra-coronal indirect restoration; it provides conservative restorations for posterior teeth since preparation for indirect restoration involves removing about 27% of intact tissues; and its mean survival rate is 90.89%. In fact, various materials ranging from resins to ceramics are used for posterior teeth indirect restorations (2).

Dental treatment has been forced under public demand to become more esthetic and faster; computer-aided design and manufacturing (CAD/CAM) has allowed clinicians to create one-visit indirect ceramic restorations (3). PEEK and its different formulations are considered a challenging indirect restorative material;

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and different literature has discussed it in recent years (4,5). BioHPP is formed from partially crystalline polyether ether ketone (PEEK) that is strengthened using ceramic. The ceramic fillers enhance its strength and abrasion properties, allowing it to be veneered. Furthermore, BioHPP achieves both rigidity and elasticity simultaneously, with critical aesthetic characteristics, due to the likelihood of being veneered (6).

In addition, compromised molars have severe structural defects after removing caries; the cavity margins are lower than the gingival margin. From a clinical point of view, it is difficult to isolate the deep margins from oral fluids such as saliva, blood, and gingival fluids to apply restorative materials. Besides, if indirect restoration is desirable, impression margin accuracy will be affected. Thus, this problem was always solved by doing a periodontal surgery through a crown lengthening procedure to relocate the gingival margin of the cavity. This technique has many drawbacks that include reducing the crown-root ratio, which renders the tooth more prone to occlusal stresses and compromises the longevity of the prosthesis (7).

Dietschi and Spreafico (8) introduced a filling method to improve the bonding of an indirect restoration with a deep sub-gingival margin. They used composite resin to raise the cavity floor to make the margin visible supra-gingival and facilitate the fabrication of the indirect restoration. This procedure was called the Sandwich Technique, when applied to proximal cavities, but later it has been known as Proximal Box Elevation (PBE) (9). Magne also used composite resin to raise the subgingival margins, and this technique is called deep margin elevation (DME). The advantages of this technique are that it can maintain the crown-root ratio, prevent tooth instability, and reduce postoperative healing time, complications, and costs (7). Flowable composite is used in the sandwich technique because a flowable material is more convenient to manipulate and adapt to the deep cavity margin than glass ionomer (10). In addition, finite element analysis (FEA) is recommended to be used in research since it imitates the environment in the oral cavity and can apply forces on the restorations mimicking the normal magnitude and direction of forces applied on the teeth in the normal clinical situation (11).

Obviously, previous research indicates a knowledge gap about stress distribution of elevated cervical margin of deep distal caries on MOD, CAD CAM indirect PEEK inlay\onlay. Therefore, we have decided to study the influence of stress distribution of elevated cervical margin of deep distal caries using flowable composite with different levelled margins on MOD, CAD CAM indirect PEEK inlay mandibular molars based on finite element analysis.

The present study evaluates the influence of indirect PEEK inlay with deep elevated cervical margin of distal caries on stress distribution in mandibular molars when a vertical and an oblique load was applied, using finite element analysis (FEA).

Methods:

The study protocol was approved by the Committee of Research Ethics, Deanship of Graduate Studies and Scientific Research, Qassim University. College of Dentistry (24-92-10).

Scanning model preparation

The tooth was requested from the surgical clinic at Qassim University. It was cleaned, sterilized, and then scanned. The tooth was extracted for routine dental treatment in college, such as periodontal, surgical, or orthodontic treatment, or purposes unrelated to this study. (12)

A GALILEOS SIRONA high-resolution CBCT (Sirona Dental Systems GmbH, Bensheim, Germany) was used to scan a fall mature, intact, human permanent mandibular first left molar. The manufacturer's instructions were followed, utilizing a 98-kV voltage and 6 mA tube current. All scans were studied in cross-sections, coronal and sagittal (axial view) in a low-light environment, from a distance of 40-50 cm away, from a 32-inch Dell LCD screen with a 1280-1024 pixels resolution, using the GALILEOS Viewer 1.9 software.

Modeling with cavity preparation for indirect inlay restoration

The MOD cavity preparation was formed by deleting the inlay volume. A further inlay- I shaped volume, having a 3.7 mm wide and 3.24 mm deep isthmus, was shaped using the FE software preprocessor (Fig 1).

In addition, three simulated models were designed with MOD cavity preparation according to the deep elevated cervical margin of deep distal caries.

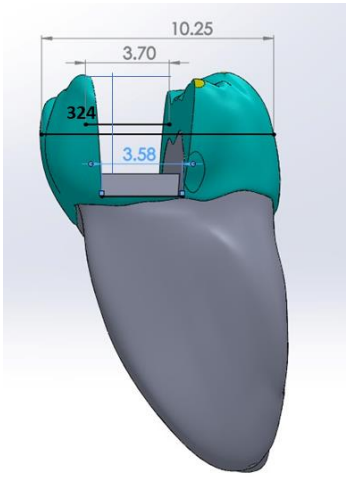


Figure 1: **MOD cavity preparation**

The first model was designed without a deep elevated cervical margin of distal caries (NEDM). The second model was designed with a deep elevated cervical margin of distal caries using flowable composite restorative materials equal to 1mm (EDM1). Moreover, the third model was designed with a deep elevated cervical margin of distal caries using flowable composite restorative materials equal to 2mm (EDM2) (Fig 2).

Before loading, Model 2 (EDM1) and Model 3 (EDM2), MOD cavity was restored with simulated flowable composite materials to build up the deep cervical distal margins, with 1mm and 2mm elevations, respectively. Then, the three models were cemented with simulated CAD CAM PEEK MOD indirect restorations.

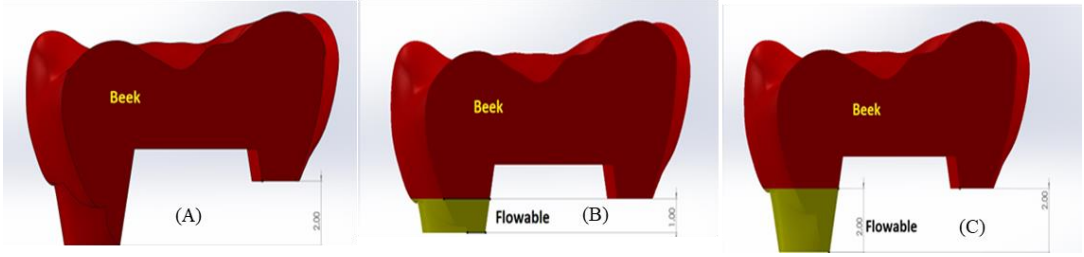


Figure 2: **Simulation of the 3 models: (A) Model 1 (NEDM); (B) Model 2 (EDM1); and (C) Model 3 (EDM2)**

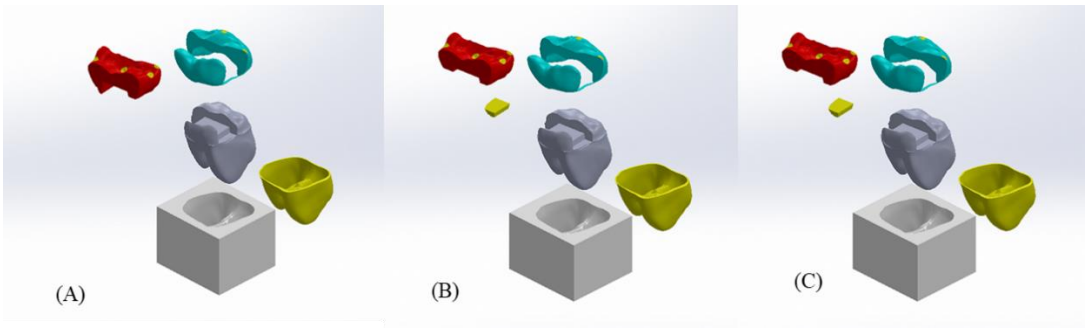


Figure 3: **Simulation of the 3 models: (A) Model 1 (NEDM); (B) Model 2 (EDM1); and (C) Model 3 (EDM2)**

Meshing and finite element analysis

The mechanical properties of the used materials (Young's modulus (GPa) and (Poisson ratio)) were listed in (Table 1). Moreover, the software's measuring tool was used to assess dimension. As a result, this helped create a 3D model that made it easier to map and move the mesh to the rapid form for building a parametric model that included an engineering drawing and a plan for finite element analysis. To improve the results of this investigation, mesh optimization was carried out; the mesh was modified to closely resemble the anatomical structures examined, making sure that larger parts did not jeopardize dependability. Smaller components, however, stayed within reasonable bounds (13). Additionally, SolidWorks 2022 software package (Dassault

Systems) was used to prepare the three designed models and mesh them in (Table 2). The tooth and all the materials used were considered homogeneous, linear, and isotropic (Fig 4 and 5 D).

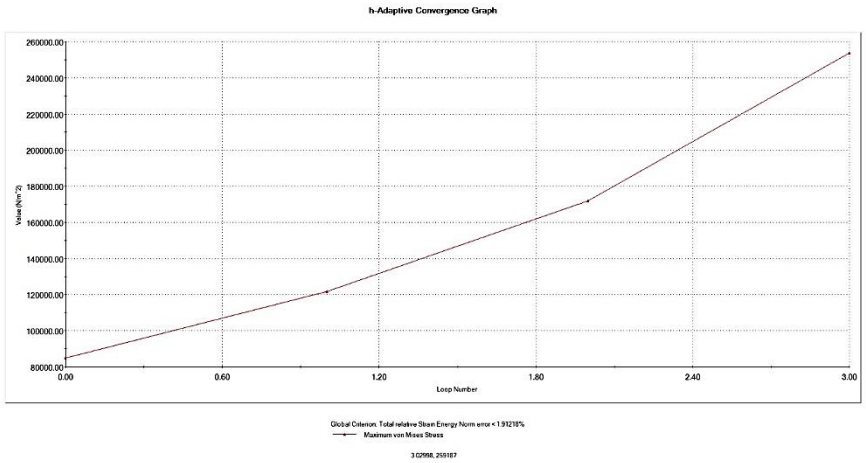


Figure 4: A daptive convergencegraph

Five occlusal contact points (mesiobuccal cusp, buccal cusp, central fossa, mesial marginal ridge, and distal marginal ridge) were defined in the three prepared models. They were exposed to the same force contact magnitude (600 N) of static occlusal load using 2 different load directions (vertical and oblique directions) (Fig 5 A,B,C). Initially, the load was directed vertically to the defined 5 points, representing the vertical masticatory force. The second load was directed MD obliquely with 45 angulations to the same defined 5 points representing lateral masticatory force.

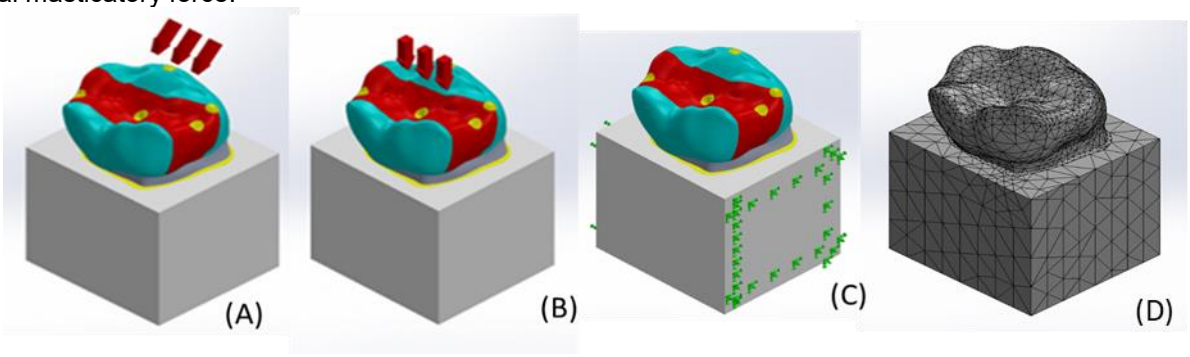


Figure 5: Simulation models with direction, amounts, and points of load distribution on the occlusal surface. (A) 600 N in the vertical direction at 5 selected yellow points; (B) 600 N in the oblique direction at 5 selected yellow points; and (C) distribution of the 5 selected yellow points model fixation. (D) meshing

Table 1: Mechanical properties of the used materials

Material	Young's Modulus (GPa)	Poisson ratio
Enamel	84.1	0.33
Dentin l	18.6	0.31
Pulp	2	0.45
Cementum	15	0.31
Cortical bone	13.7	0.3
Cancellous bone	1.37	0.31
Periodontal ligaments	68.9	0.45
Flowable composite	7.98	0.32

PEEK	3.8	0.38

Table 2: Meshing parameters

Model	Number of elements	Number of nodes
NEDM	55992	93154
EDM1	54298	19080
EDM2	54297	91135

After the load was applied to the three models, (NEDM), (EDM1), and (EDM2), in both load directions, analysis of the maximum von Mises (VM) stresses and stress distribution patterns were calculated mathematically using FEA (Table 2).

The evaluated area was at the external surface of occlusal (mesiobuccally, central fossa, mesial isthmus, and distal isthmus area) and the cervical margin was on both the mesial and distal surfaces. Furthermore, the evaluation included all materials (enamel, dentin, flowable composite elevated deep margin, and CAD CAM PEEK indirect inlay restoration).

Results

The FEA color maps were studied. The highest values were dark red; and the lowest ones were dark blue. Figures 8,9,10, and 11 show the stress distribution in the three models in different layers and surfaces of tooth structures, restorations, and surrounding tooth structures.

First, stress distribution in tooth structure and surrounding structures:

The values of von Mises stress were studied in different layers of the 3 models (enamel, dentin, and restoration) and the surrounding structures (periodontal tissue, spongy bone, and periodontal ligament (PDL)). All vertical and oblique load results were recorded in the tables and diagrams below (Tables 3 & 4 and Figures 6 & 7).

In general, the highest concentrated stress in all tooth structures and surrounding structures was found with an oblique load. Furthermore, enamel had the highest concentrated stress in all tooth structures and surrounding structures. In Model 1, it was found that dentin had the highest concentrated stress with an oblique load, in comparison to the other models. On the other hand, in Model 2, enamel had the highest concentrated stress with an oblique load. Moreover, with the oblique load, it was found that Model 2 had the highest concentrated stress at PDL. Additionally, Model 1 had the highest stress at the cancellous bone and gingival steps (mesial and distal). Regarding the vertical load, it was found that Model 2 had the highest concentrated stress at the enamel and mesial surfaces of the gingival step, while Model 1 had the highest concentrated stress at the dentine, cancellous bone, and mesial surface of the gingival step. Finally, Model 3 had the highest concentrated stress at PDL.

Second, indirect inlay and flowable restoration stress distribution (Tables 3&4 and Figures 6&7).

In general, the highest concentrated stress in all restorations was found with the oblique load; and the highest concentrated stress in indirect restoration contact points was in Model 1. Model 3 had the highest concentrated stress with PEEK restoration, flowable restoration, fitting surface of PEEK indirect restoration, and indirect PEEK inlay with oblique load. In contrast, Model 1 had the highest concentrated stress contact points in indirect PEEK restoration.

In addition, regarding the vertical load, it was found that Model 1 had the highest concentrated stress with indirect restoration contact points. Moreover, Model 3 had the highest concentrated stress with PEEK restoration, flowable restoration, fitting surface of PEEK indirect restoration, and mesial and distal surfaces of PEEK indirect restoration.

Table 3: Vertical von Mises stresses (MPa) values on tooth structure, gingival step (mesial and distal), and indirect restorations.

Model	Tooth structure, PDL, bone, and gingival step					Restorations			
	Enamel	Dentine	PDL	Cancellous	Gingival step	Indirect restoration	Flowable restoration	Fitting surface of PEEK	PEEK indirect

				s bone	M esial	D istal	on contact points	on	indirect restoratio n	restorat ion (m esial & distal)
M odel 1	3 24.4	13 1.15	1 0.77	25 .54	7 1.18	1 9.67	206 .17	-	17.3 4	17 .07
M odel 2	3 40.4	12 8	1 2.75	25 .22	7 0.88	1 8.25	191 .05	34. 3	17.5 7	17 .57
M odel 3	3 35.85	10 8.34	1 2.82	25 .29	4 7.58	1 6.83	186 .8	34. 38	18.1 1	18 .11

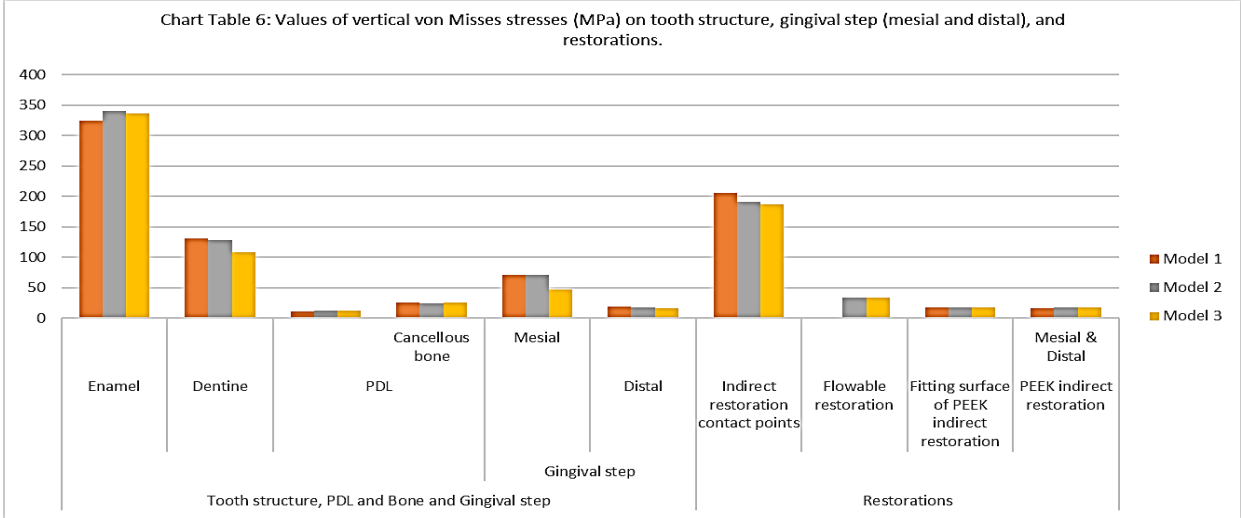


Figure 6: von Mises stresses (MPa) on tooth structure, gingival step (mesial and distal), and restorations, when oblique load was applied

Table 4: Values of oblique l von Mises stresses (MPa) on tooth structure, gingival step (mesial and distal), and restorations.

	Tooth structure, PDL, bone, and gingival step						**Restorations**			
	En amel	De ntine	P DL	Ca ncellou s bone	Gingival step Mesial	Distal	Indi rect restorati on contacts points	Flo wable restorati on	Fit ting surf. of PEEK	P EEK (m esial & distal)
M odel 1	49 3.45	19 9.65	2 3.84	50 .16	12 1.43	51. 67	241 .43	-	29 .98	29 .98
M odel 2	61 8.44	19 4.99	2 5.7	47 .99	11 9.35	49. 96	225 .61	27. 56	33 .94	33 .94
M odel 3	61 8.1	16 6.05	2 5.17	48 .05	11 7.25	36. 35	226 .96	33. 69	34 .36	34 .36

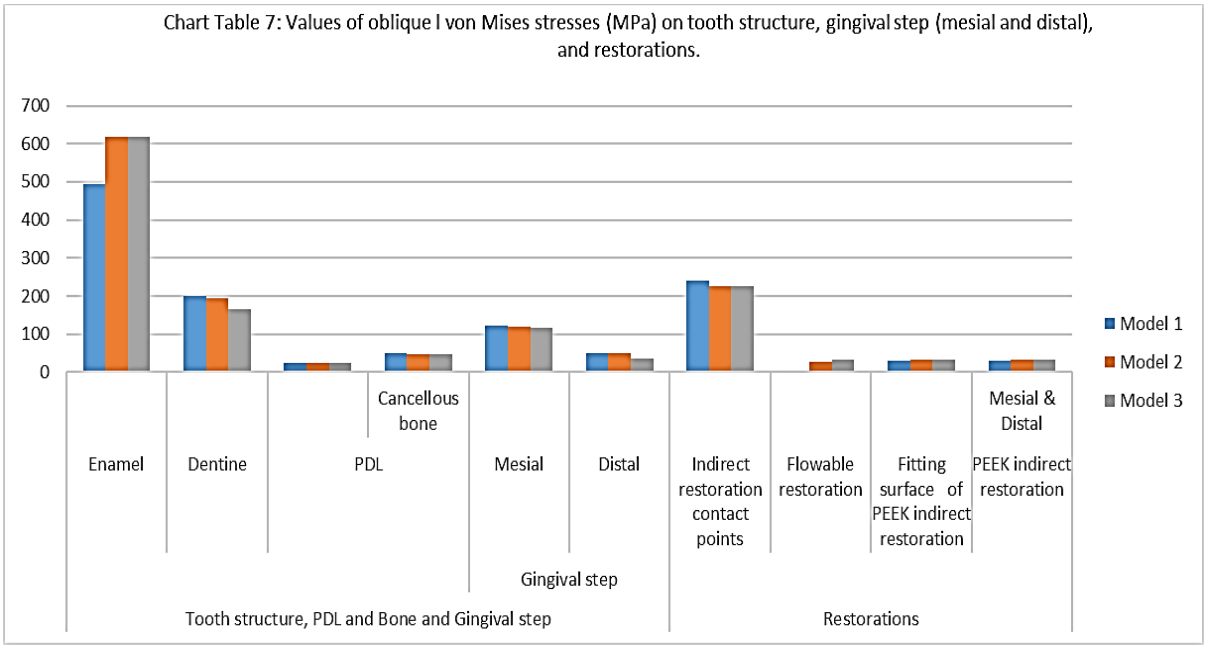


Figure 7: von Mises stresses (MPa) on tooth structure, gingival step (mesial and distal), and restorations, when oblique load was applied.

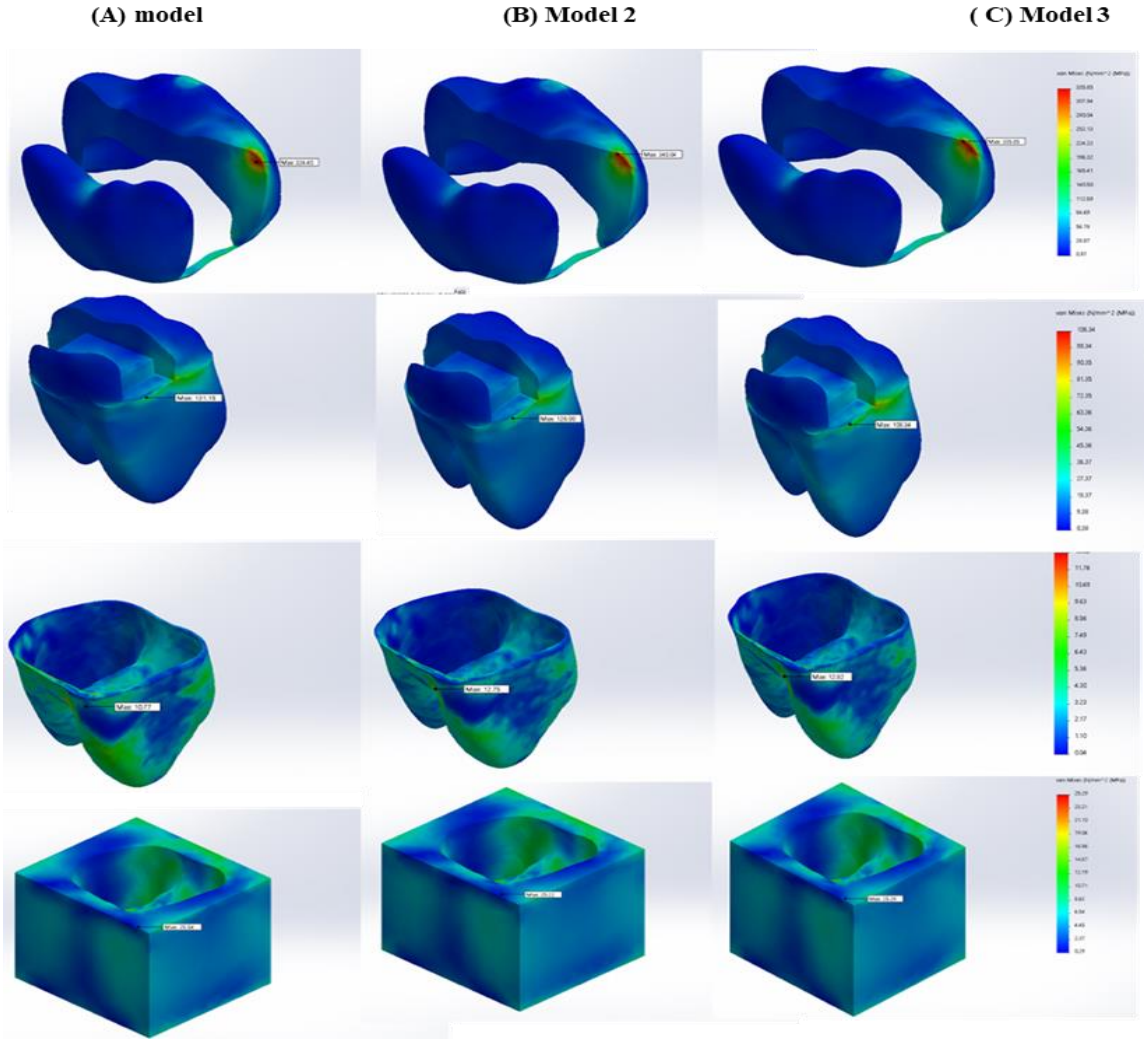


Figure 8: Stress distribution in enamel, dentin, PDL, and bone with vertical load in CAD CAM indirect PEEK in Model 1 (A), Model 2 (B), and Model 3 (C).

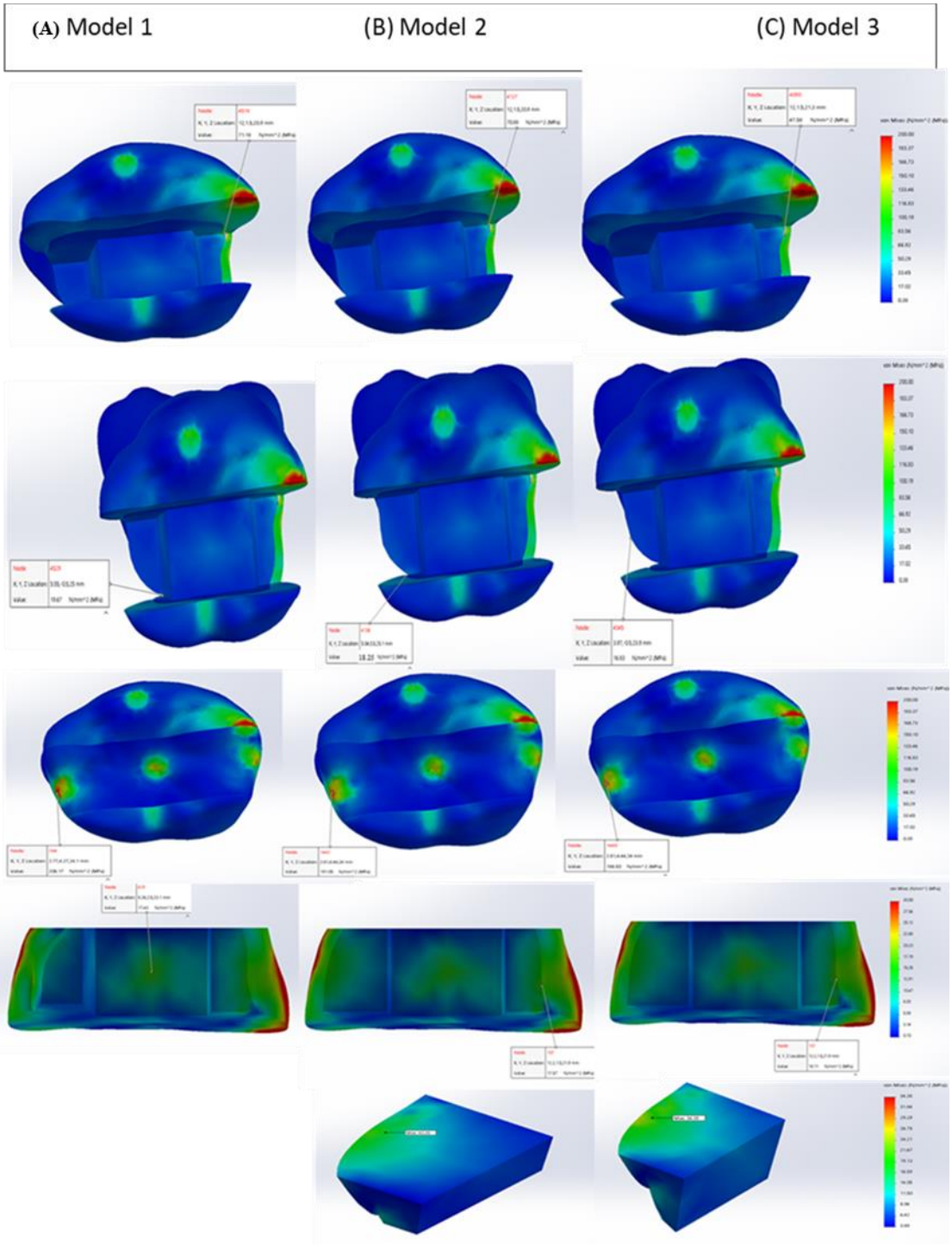


Figure 9: Stress distribution in mesial, distal, and fitting surfaces with vertical load in CAD CAM indirect PEEK in Model 1 (A), Model 2 (B) and Model 3 (C)

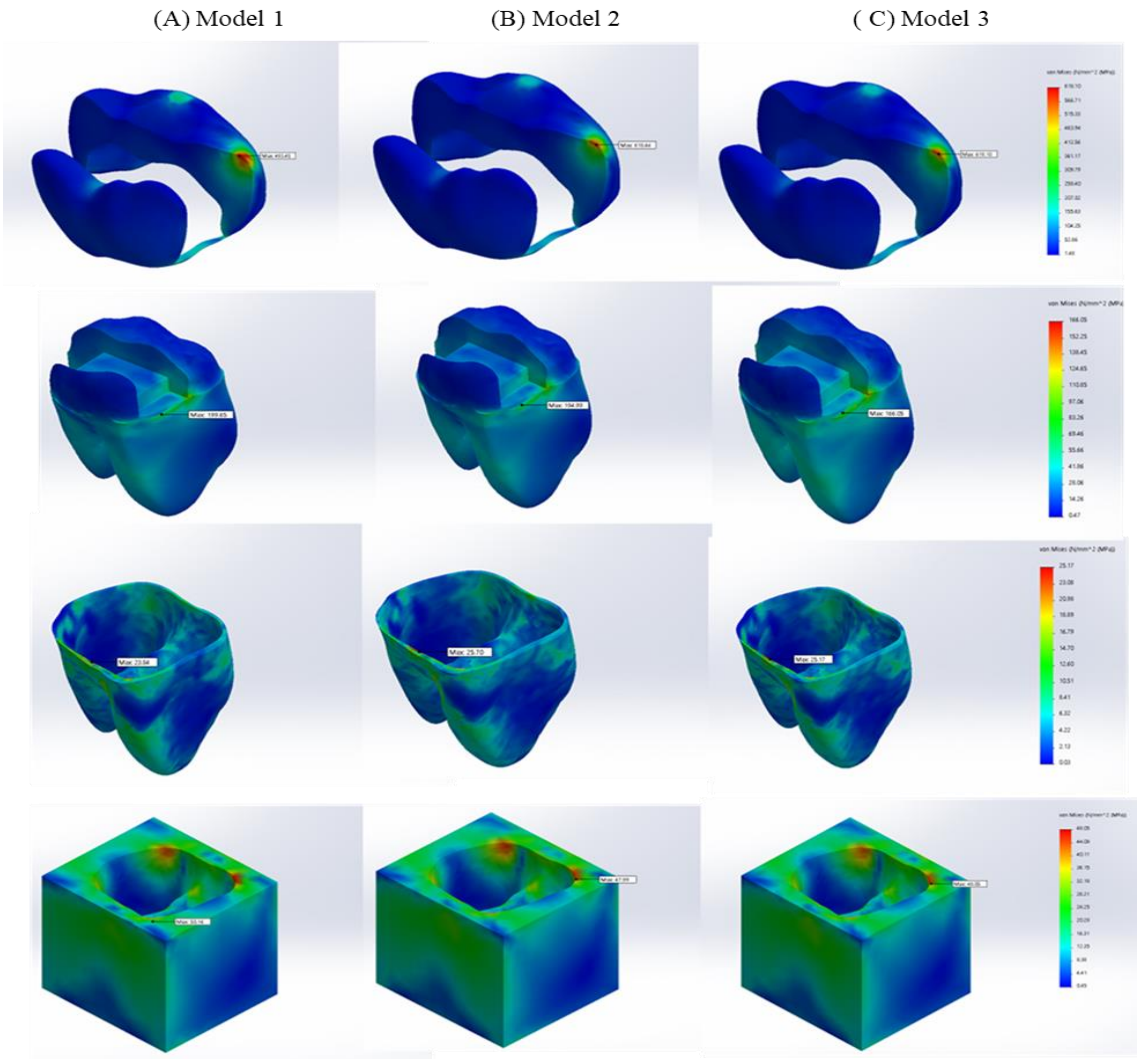


Figure 10: Stress distribution in enamel, dentin, PDL, and bone with oblique load in CAD CAM indirect PEEK in Model 1 (A), Model 2 (B), and Model 3 (C).

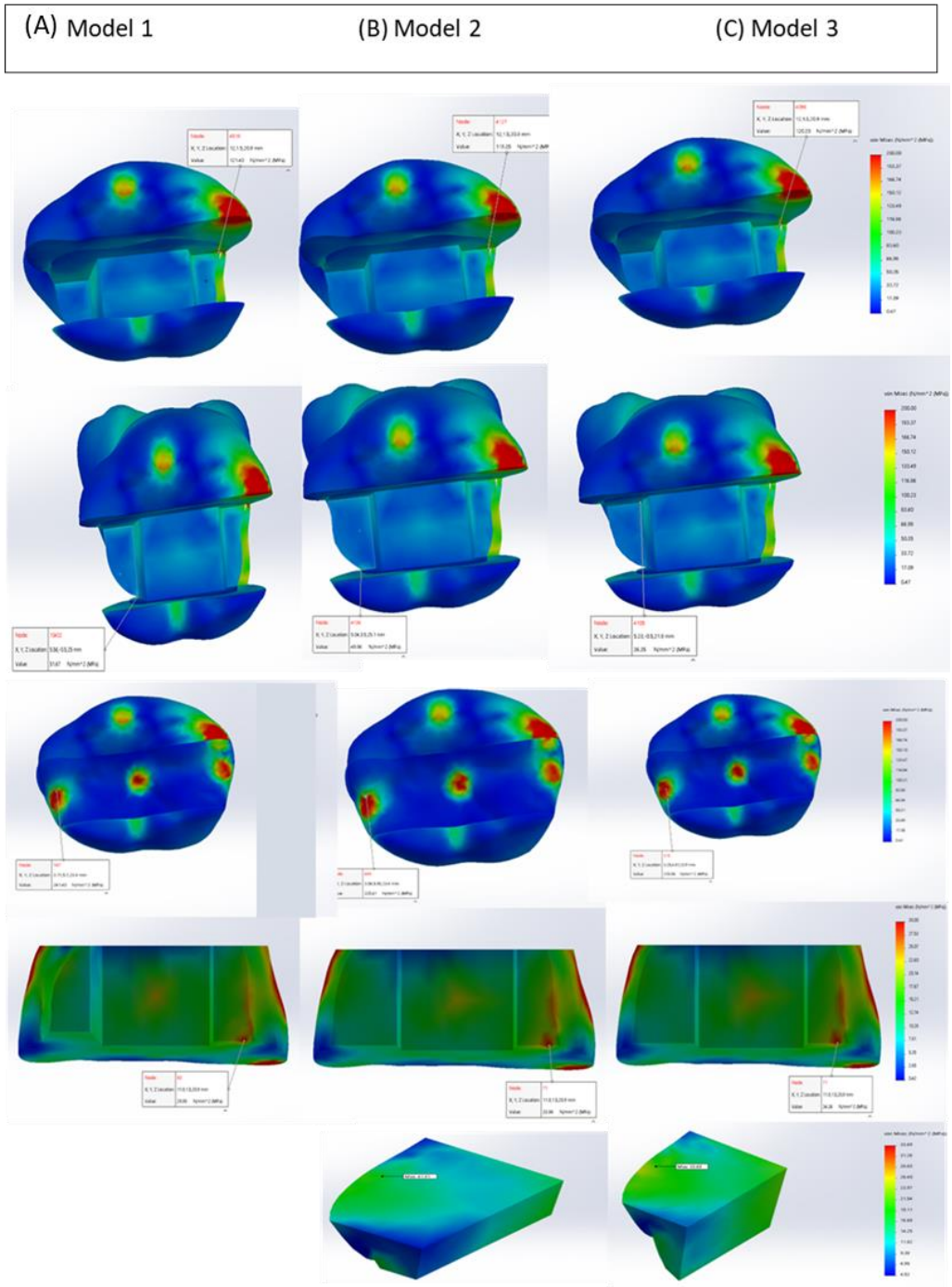


Figure 11: Stress distribution in mesial, distal, and fitting surfaces with oblique load in CAD CAM indirect PEEK in Model 1 (A), Model 2 (B), and Model 3 (C).

Discussion

Finite element analysis has been used widely in different fields of dentistry (12,14). As a result of the improvement in 3D reconstruction technology, biomechanical assessments can be done on realistic human anatomy to reduce clinical and animal trials (15). Moreover, FEM is considered an essential tool in research, where researchers can determine stress distribution in teeth and restorations under various circumstances (16). Thus, von Mises stresses were used in the current study to calculate stresses. All stresses (tensile, compressive

and shear stresses) were calculated in the entire stress field, which was I considered an indicator of possible failure and its location (17). This study has aimed to assess the effect of deep margin elevation with CAD CAM indirect PEEK inlay on stress distribution in mandibular molars when applying vertical and oblique loadings. Additionally, MOD cavities in mandibular molar models have been used since posterior teeth are more prone to losing hard tissues due to caries, restoration failure, or endodontic procedures (1).

Functional and parafunctional forces of different directions and magnitudes also fall on molar teeth (1). The maximum biting force ranges from 200 N to 3,500 N, depending on many factors such as the occlusion scheme, the restorations, and the tooth position. The bite force normally falling on molars ranges from 400 to 800 N (18). Consequently, an average force of 600 N was used in this study. Vertical loading was applied to stimulate the normal force on mandibular molars, whereas oblique loading was applied to stimulate the clinical force on mandibular molars through the mastication closing phase (1).

This study has shown that oblique forces resulted in higher stress values and more stress concentrations in dental tissues and restorations, in comparison to vertical forces, in the three models. These results match the findings of previous studies by Mei et al. and Yamanel (18,19). Moreover, it emphasizes previous finding that nonaxial forces may cause the worst prospective damage in restorations (20). The outcomes of the current study also show that von Mises stresses at the gingival step, either at the mesial or distal side, are the highest in (Model 1), followed by (Model 2), and then (Model 3). This could be related to the findings by Gonder et al. (21). In addition, materials with a low elastic modulus transfer more stress to tooth structures; and the PEEK restoration has an elastic modulus (3.8 GPa), while the flowable composite has an elastic modulus (7.98 GPa).

These findings expose a potential benefit of deep margin elevation beneath ceramic inlays; a direct restoration on the gingival step shortens the occlusal-gingival height of the proximal part of the inlay. Based on the data found in this study, shorter heights of proximal ceramic inlays are associated with less vertical and oblique stresses. This is compatible with the findings of Vertolli (22), which state that to keep survival rates above 90% for ceramic inlays at five years of service, clinicians should consider deep margin elevation when the proximal box is greater than 5mm in occlusal-gingival height. These results also coincide with Baldi et al. (23), who have found that using a flowable composite as a liner on the cervical margin significantly reduces shear stresses and normal pressure on the cervical margin area.

Moreover, the color maps showed that the maximum stresses were at the loading point in the buccal margin of inlays at the mesio-buccal cusp in indirect PEEK or in adjacent enamel in the three models; this result is in agreement with the results of earlier studies by Darwich et al. (12), and Degak and Mtotkowski (24). The location of the loading points might contribute to explaining this result. Besides, the damage would likely occur at the tooth-indirect PEEK interface since loadings were not completely applied to the indirect PEEK but partially to the tooth structures (12,19).

Regarding the inlay material, one of the essential reasons for PEEK to be chosen in this study is that it exhibits low Young's modulus (3 to 4 GPa), and it is as elastic as bone, providing a cushioning effect which results in a more balanced stress distribution and reduces stresses transferred to the tooth (25). Furthermore, the results of the PEEK fitting surface revealed that the highest stress value was recorded on the fitting surface of PEEK in Model 3, followed by the fitting surface of PEEK in Model 2, then the fitting surface of PEEK in Model 1. This might be due to restoration thickness and volume since the increase in the thickness and volume of the restoration resulted in a better pattern of stress distribution (16); these findings are in line with the conclusions of previous studies by Durand et al. (26) and Darwich et al. (27).

In addition, Model 1 had the lowest stresses on the PEEK restoration under vertical and oblique loads. In contrast, it had the highest stresses on the gingival step, on the mesial and distal sides, under vertical and oblique loads. This could be explained by the findings of Gonder et al. (21) stating that low elastic modulus materials transfer more stresses to tooth structures, and PEEK restoration has a low elastic modulus (3.8 GPa).

Finite Element Analysis (FEA) can forecast the distribution of stress across most elements of the prostheses following the application of load (28). However, its effectiveness is constrained by theoretical assumptions, particularly regarding the specified loading and boundary conditions used to model the required loading scenarios, as well as the uniformity of material properties. This limitation can influence the precision of the analytical results pertaining to biomechanical stress conditions .

Given the limited linear numerical findings of this research, the results from FEA are only capable of offering a relative assessment of the biomechanics of the components within the tooth-implant fixed dental prostheses system under average circumstances. Therefore, it is recommended that future validating studies (in-silico) on this relevant topic be conducted.

Conclusions

Within the limitations of this study, we can conclude that badly broken-down molars restored with PEEK CAD CAM indirect inlay\ onlay, 2mm elevated cervical margin of the deep distal cavity using flowable composite

have the lowest stress on the gingival step, when compared with applying 1mm elevated cervical margin of the deep distal cavity using flowable composite and PEEK inlay\onlay cervical margin of the deep distal cavity.

Declarations

●**Abbreviations:**

- Finite element analysis (FEA)
- Mesio occlusal Distal (MOD)
- designed without a deep elevated cervical margin of distal caries (NEDM)
- deep elevated cervical margin of distal caries to 1mm (EDM1).
- deep elevated cervical margin of distal caries to 2mm (EDM2)

●**Ethics approval:** The study protocol was approved by the Committee of Research Ethics, Deanship of Graduate Studies and Scientific Research, Qassim University. College of Dentistry (24-92-10).

●**Consent to participate:** Not applicable

●**Consent to publish from the patient:** Not applicable

●**Consent for publication:** All authors of the research agree to publish.

●**Availability of data and materials:** The material and data and has not been reproduced from another source; all of the material is owned by the authors an no permissions are required.

●**Competing Interests:** There is no conflict of interest related to this submission.

●**Funding:** Self-fund

●**Authors' contributions:** Each author contributed to all steps of the research, from ideas and information gathering to writing, analyzing and interpreting the results and reviewing them.

● **Acknowledgements:** Not applicable

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