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Original research

THE EFFECTS OF DIFFERENT BASE MATERIALS ON THE STRESS DISTRIBUTION OF THE ENDODONTICALLY TREATED TEETH: 3D FEA

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ABSTRACT

Objectives: This study evaluated stress distrubitions formed by oblique forces in dental hard tissues, base materials and restorations of endodontically treated permanent mandibular first molars that were restored with different base materials and direct composite restorations by using 3D-FEA method.

Materials and Methods: For two different restorative approaches; an MO cavity design and a MOD cavity design was created. Then root canal obturation was modeled. Composite resin (CR), conventional glass ionomer cement (GIC), fiber reinforced composite resin (FRC), resin modified glass ionomer cement (RMGIC), flowable composite (FC), and bulk-fill composite resin (BF) were used as base materials. Von Mises, compressive and tensile stresses in enamel, dentin, base materials and final restoration were analyzed using finite element stress analysis method.

Results: Regarding the resulting stresses, CR caused highest stresses and RMGIC caused lowest stresses in enamel, base material, and final restoration. RMGIC caused highest stresses and CR caused lowest stresses in dentin. It was noted that MOD cavity design caused more stress than MO cavity design for all analyzed materials.

Conclusions: Materials with elastic moduli similar to dentin; FRC and GIC, may be better choice to avoid high stresses within the tooth and restoration.

Keywords: Composite resins, glass ionomer cements, finite element analysis.

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INTRODUCTION

Following endodontic treatment, teeth should be protected against chewing forces because they become prone to fracture.[1,2] Many restorative materials and techniques are available for the reconstruction of the endodontically treated teeth. It should be noted that the restoration must protect the tooth against the chewing forces by distributing the stress throughout the supporting tissues. To withstand masticatory forces in the oral cavity, the elastic modulus of the restorative material is an important factor and its role in the longevity of the final restoration is crucial. The elastic modulus of the restorative material should be close to the tooth structure.

Some investigators have showed that oblique forces created much more intense stress than vertical forces during mastication.[3,4] The restoration must minimize the loss of dental hard tissue and restorative material used by distributing the stress produced by oblique forces.[2] Restorative materials and changes in tooth structure are some of the factors that increases risk of failure.[1,5]

3D finite element analysis (3D FEA) has been widely used by many researchers to evaluate the effects of restorative materials on stress distribution.[6–8] It is also an effective way to evaluate the biomechanical characteristics of dental restorative materials, and the results of the analysis shows clinical significance.[8–10]

In the dental literature, too many studies have been done to evaluate the effects of base materials on stress distribution using 3D FEA, but the information about fiber reinforced composites as base materials is too limited. Therefore, the aim this study was to evaluate the stress distributions formed by oblique forces in dental hard tissues after restoration of endodontically treated teeth with different base materials including fiber reinforced composites with 3D FEA.

MATERIALS AND METHODS

A 3-dimensional (3D) main model was designed to represent an endodontically treated mandibular first molar tooth. The geometry used for the tooth model was previously described by Wheeler Atlas of Anatomy.[11] A simplified 0,25-mm-width periodontal ligament (PDL), 0,25-mm-width lamina dura and cortical shell were developed. The simulated PDL and alveolar bone structure were added to the main model. The remaining bone was modeled as trabecular bone (Figure 1a).

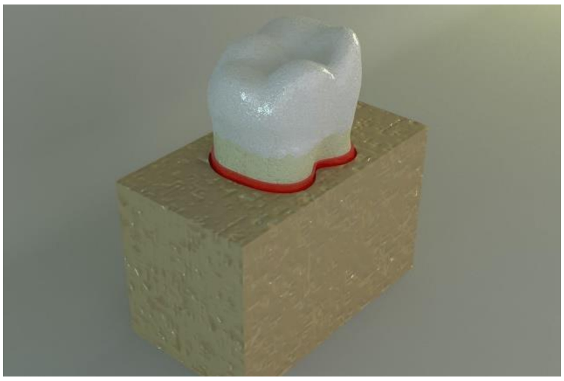

Figure 1a. Designed model; tooth structure, periodontal ligament and alveolar bone.

Two different submodels were designed to evaluate the effects of cavity preparation on the stress distribution: a mesio-occlusal (MO) cavity design and a mesio-ocluso-distal (MOD) cavity design (Figure 1b,c).

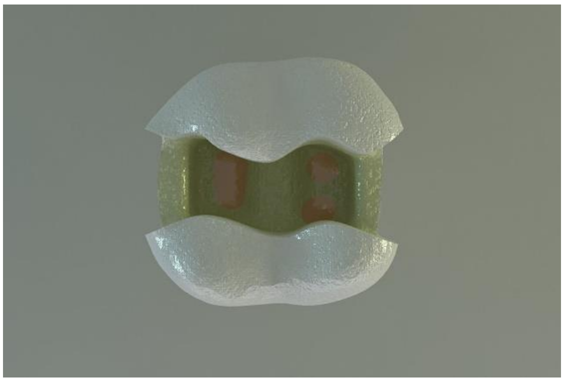

Figure 1b. Designed model; MOD cavity design.

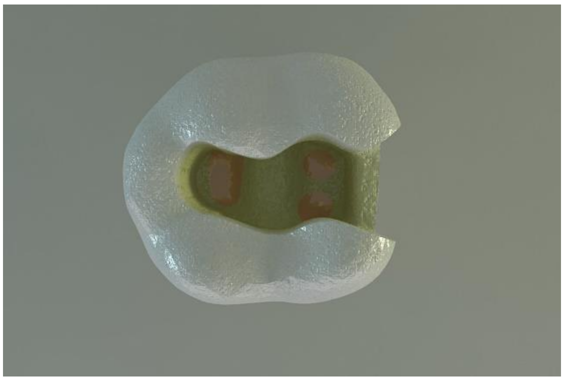

Figure 1c. Designed model; MO cavity design.

Cavity preparations were created by deleting the overlapping tooth and restoration volume. MO and MOD cavity designs were created with 8-mm cavity depth, 3-mm isthmus width, and 2-mm gingival wall width. Twelve different models were investigated to evaluate six different type of base material. 2 of these models were directly restored with composite resin (CR). For the other models, base materials were designed as conventional glass ionomer cement (GIC), fiber reinforced resin composite (FRC), flowable resin composite (FC), resin modified glass ionomer cement (RMGIC), and bulk-fill resin composite (BF). All the restorations were finished with the use of one type of composite resin. The elastic moduli and Poisson's ratios of restorative materials, enamel, dentin, trabecular and cortical bone, and gutta percha were introduced, also the brands of materials designed in this study are listed in Table 1.

Table 1. Properties of materials and dental tissues

	Brand Name	Manufacturer	Elastic Modulus (GPa)	Poisson's Ratio(v)
FRC[12)]	EverX Posterior	GC, Tokyo, Japan	12.3[a]	0.31[a]
BF[13)]	SDR	Dentsply, Konstanz, Germany	4.7	0.4
GIC[14)]	Fuji IX	GC, Tokyo, Japan	12.6	0.3
RMGIC[7)]	Vitrebond	3M ESPE, St Paul, MN, USA	3.7	0.36
FC[15)]	Tetric Flow	Ivoclar Vivadent, Schaan, Liechtenstein	5.3	0.28
CR[16)]	Grandio	Voco, Cuxhaven, Germany	20.4	0.33
Gutha Percha[17)]			0.14	0.45
Cortical Bone[17)]			13.7	0.3
Spongious Bone[17)]			1.37	0.3
Dentine[17)]			20	0.31
Enamel[17)]			46.8	0.3

[a] Data provided by the manufacturer (GC, Tokyo, Japan)

Rhinoceros 4.0 software was used to obtain tooth models and these models meshed for analysis in Algor Fempro software (ALGOR, INC. 150 Beta Drive Pittsburgh, PA, USA) in STL format. As a result of meshing, models composed of 10-node point (brick-type) units were created. Regarding the bounds of the program, excessive number of units for all dimensions of the tooth models were selected to obtain most realistic results. A MO cavity designed model with 51950 nodes and 274431 elements, and MOD cavity designed model with 60889 nodes and 296933 elements were used. All components were assumed to be in contact with one another for identification of surface relationships among the model's parts and analysis of the mathematical models. Zero motion and rotation were identified at six degrees of freedom from the side and upper surfaces of dental tissues.

An oblique loading of 240N with 45° was applied to central fossa, distal marginal ridge, mesiobuccal cusp tip, and distobuccal cusp tip (60N for each point) (Figure 2).[18]

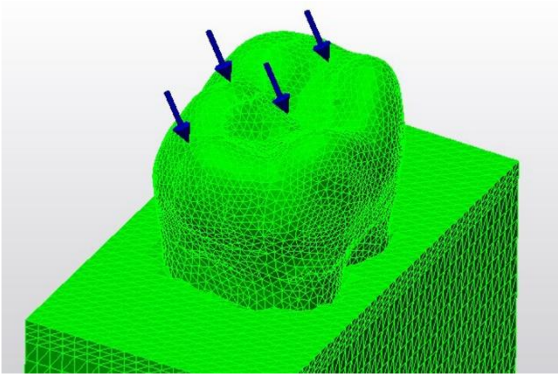

Figure 2. Applied forces.

For each twelve models, 3-D finite element analysis was used to evaluate von Mises stress, maximum principle stress (tensile) and minimum principle stress (compressive) on the restorative materials, base materials, enamel and dentin. Besides of that, different points were selected on dentin and base materials to compare stresses occurred with different base materials and cavity designs. Three of this selected points were located on the gingival walls of MOD and MO cavity designs (Figure 3a,b) and two of them were located on the upper and lower surfaces of the base materials (Figure 3c,d).

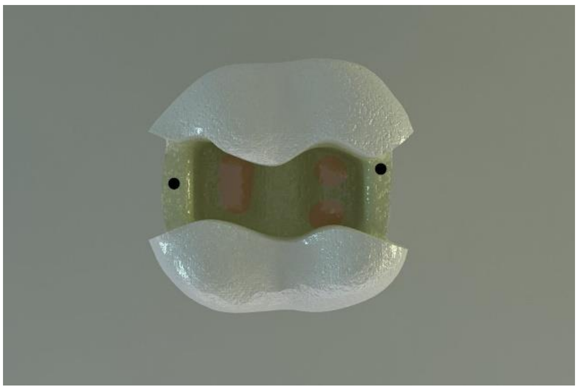

Figure 3a. Selected points for von Mises, compressive and tensile stress analyzes; dentine of MOD cavity design.

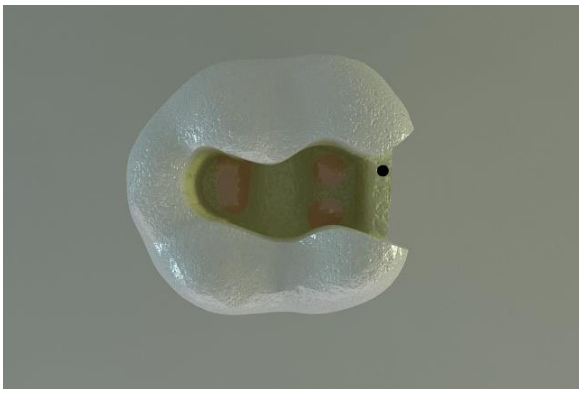

Figure 3b. Selected points for von Mises, compressive and tensile stress analyzes; dentine of MO cavity design.

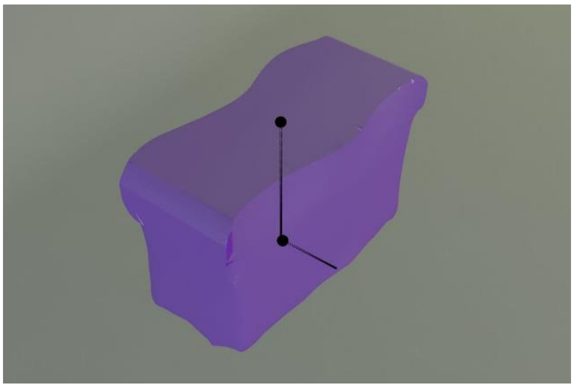

Figure 3c. Selected points for von Mises, compressive and tensile stress analyzes; base material of MOD cavity design.

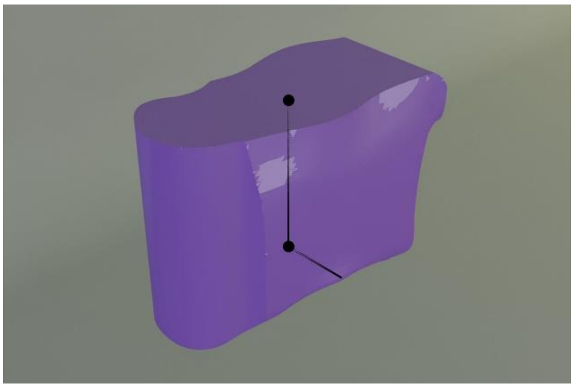

Figure 3d. Selected points for von Mises, compressive and tensile stress analyzes, base material of MO cavity design.

RESULTS

Stress Analysis in Enamel

Von Mises stress distributions occurred in enamel after oblique force application found to be very similar for both cavity types, the high stress areas were concentrated on the lingual cervical area and distobuccal cusp tip (Figure 4a-d).

Regarding the stresses occurred in final restoration material, stress distributions were found to be similar for both cavity design, and high stress areas were concentrated in lingual area of the final restoration and differences were observed in neighboring gingival wall areas. Stress distributions on this area showed higher

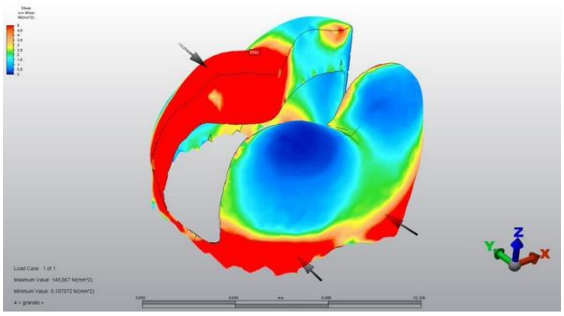

Figure 4a. Highest and lowest von Mises stresses in enamel for MOD-CR design.

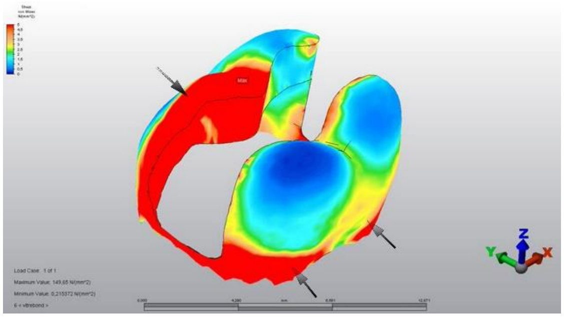

Figure 4b. Highest and lowest von Mises stresses in enamel for MOD-RMGIC design.

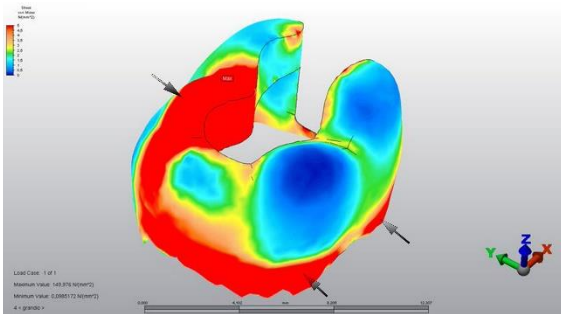

Figure 4c. Highest and lowest von Mises stresses in enamel for MO-CR design.

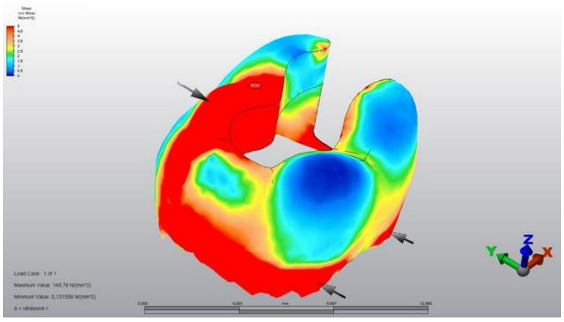

Figure 4d. Highest and lowest von Mises stresses in enamel for MO-RMGIC design.

values in CR models, and lower values obtained in RMGIC models (Figure 5a-d).

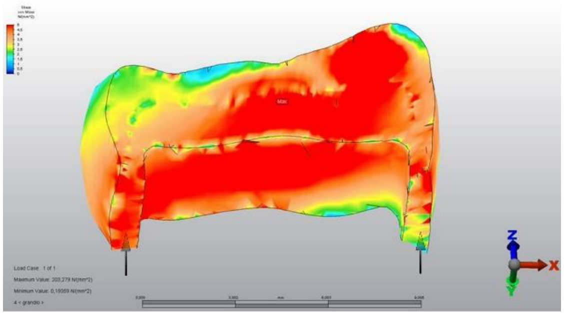

Figure 5a. Highest and lowest von Mises stresses in final restoration for MOD-CR design.

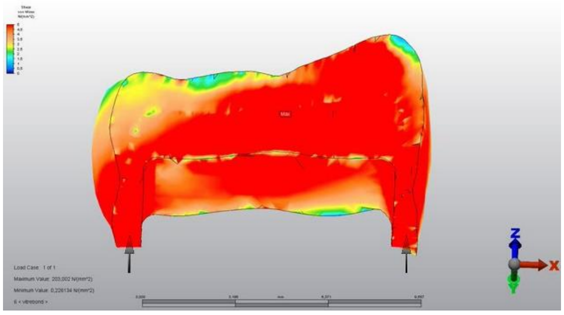

Figure 5b. Highest and lowest von Mises stresses in final restoration for MOD-RMGIC design.

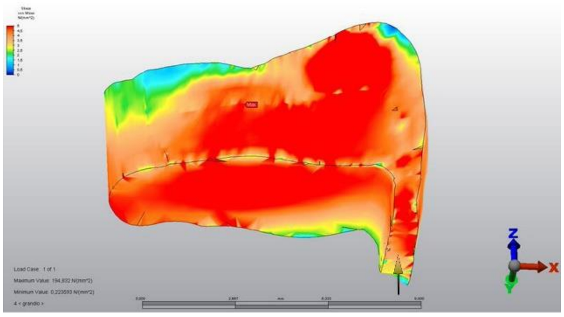

Figure 5c. Highest and lowest von Mises stresses in final restoration for MO-CR design.

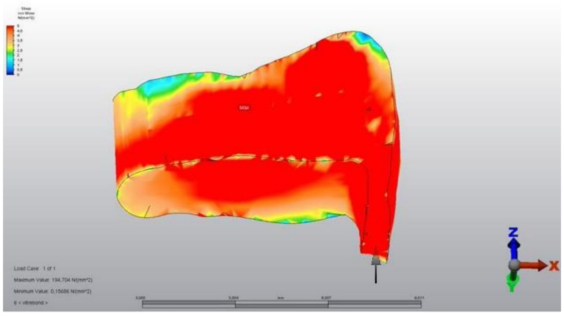

Figure 5d. Highest and lowest von Mises stresses in final restoration for MO-RMGIC design.

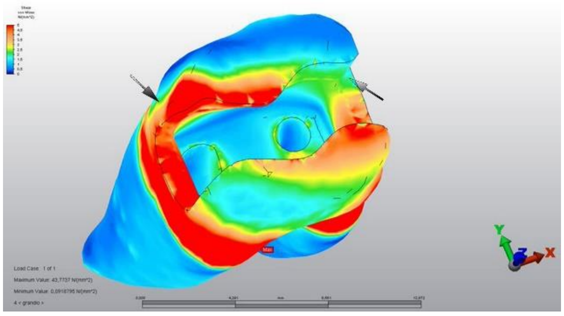

Figure 6a. Highest and lowest von Mises stresses in dentin for MOD-CR design.

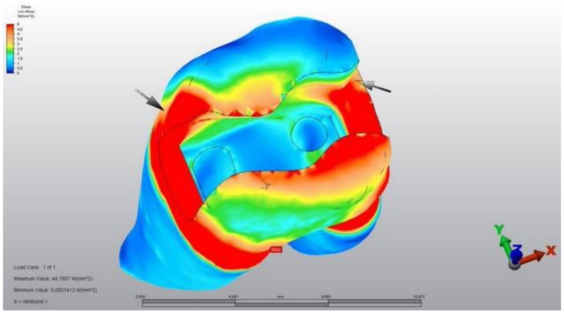

Figure 6b. Highest and lowest von Mises stresses in dentin for MOD-RMGIC design.

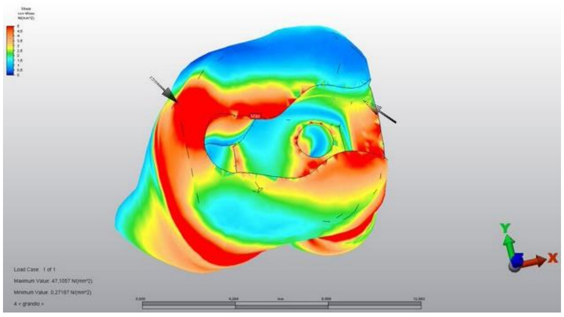

Figure 6c. Highest and lowest von Mises stresses in dentin for MO-CR design.

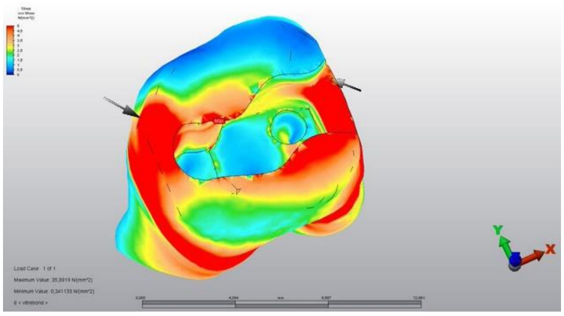

Figure 6d. Highest and lowest von Mises stresses in dentin for MO-RMGIC design.

When von Mises stress distributions were evaluated according to the type of base material, differences were observed in dentine for both cavity designs (Figure 6a-d).

The highest von Mises stress values were observed in CR models and the lowest von Mises stress values were found in RMGIC models. Regarding selected points on dentine, the highest von Mises and compressive stress values were observed in RMGIC models and the lowest values observed in CR models (Table 2).

Table 2. von Mises, compressive and tensile stress values (MPa) on the selected points of MOD and MO cavity design.

	von Mises			Compressive			Tensile		
	MO - MGW	MOD-MGW	MOD-DGW	MO - MGW	MOD-MGW	MOD-DGW	MO - MGW	MOD-MGW	MOD-DGW
CR	3.0080	2.2781	5.1823	-2.2533	-1.8834	-4.5647	1.1258	0.6164	1.2141
GIC	3.6348	2.7731	6.0319	-2.7528	-2.2897	-5.2836	1.3210	0.7551	1.4403
FRC	3.6763	2.8054	6.0824	-2.7696	-2.3011	-5.3026	1.3555	0.7890	1.4870
FC	4.8608	3.7857	7.6924	-3.7044	-3.0851	-6.6316	1.7405	1.1034	1.9673
BF	5.1372	4.0519	7.9453	-3.6659	-3.0439	-6.5076	2.1558	1.5521	2.4893
RMGIC	5.4156	4.2892	8.3824	-3.9880	-3.3304	-6.9982	2.1224	1.4976	2.4518

(MO -MGW: MO cavity mesial gingival wall, MOD-MGW: MOD cavity mesial gingival wall, MOD-DGW: MOD cavity distal gingival wall)

The highest tensile stress values were obtained in BF models and the lowest stress values were obtained in CR models (Table 2). When cavity designs were compared, the highest stress values observed in distal gingival wall of MOD cavity design and the lowest stress values observed in mesial gingival wall of the MOD cavity design.

When stress distributions in base materials were evaluated, it is noted that high stress areas were concentrated on the occluso-lingual side of the base materials for all material types and cavity designs (Figure 7a-d).

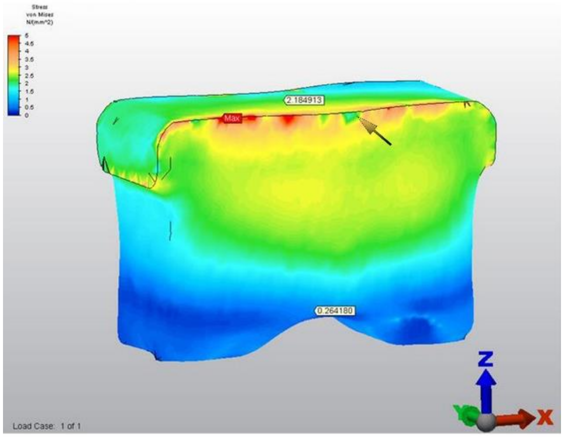

Figure 7b. Highest and lowest von Mises stresses in base material for MOD-RMGIC design.

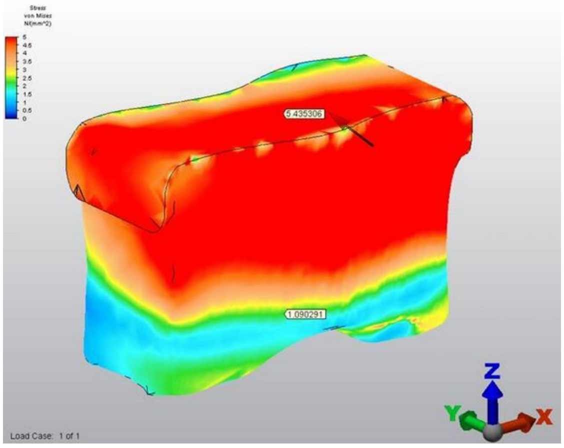

Figure 7a. Highest and lowest von Mises stresses in base material for MOD-CR design.

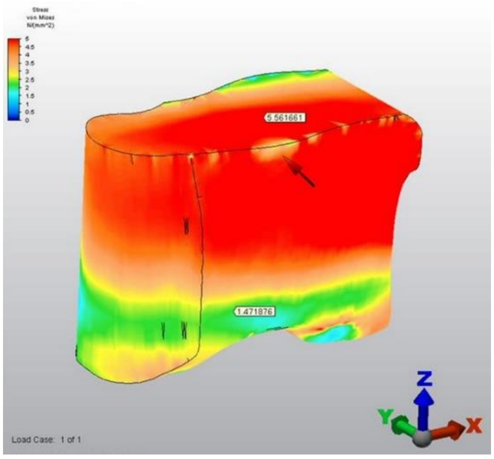

Figure 7c. Highest and lowest von Mises stresses in base material for MO-CR design.

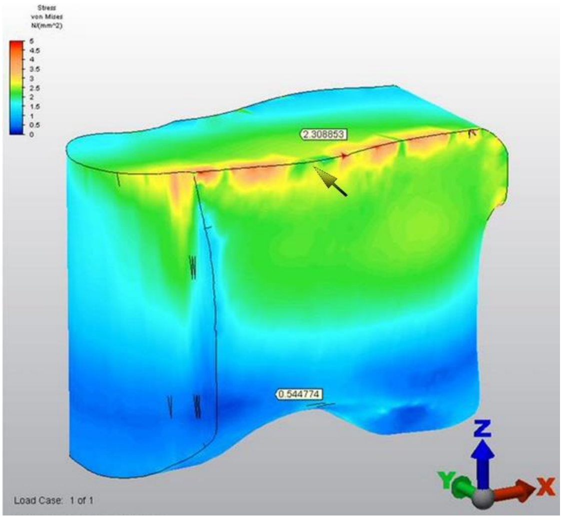

Figure 7d. Highest and lowest von Mises stresses in base material for MO-RMGIC design

Stress distribution differences were observed for both cavity designs regarding base material type. The highest von Mises stress values were observed in CR models and the lowest values were observed in RMGIC models for both cavity type. When selected points on base materials were evaluated, differences were observed regarding the base material type and cavity design. The highest von Mises, compressive, and tensile stress values were obtained in CR models and the lowest von Mises and compressive stress values were obtained on RMGIC models for both cavity type. However, in MOD cavity lower surface the lowest compressive stress value was obtained in FC model (Table 3).

Table 3. von Mises, compressive and tensile stress values (MPa) on the selected points of base materials.

	von Mises				Compressive				Tensile			
	MOD-US	MOD-LS	MO-US	MO -LS	MOD-US	MOD-LS	MO -US	MO -LS	MOD-US	MOD-LS	MO -US	MO -LS
CR	5.4353	1.0902	5.5616	1.4718	-5.0346	-0.9184	-5.0332	-1.7750	0.9073	0.3385	0.9972	-0.1484
GIC	4.6744	0.7036	4.6747	1.1239	-4.4008	-0.8962	-4.3239	-1.6004	0.7013	-0.0950	0.7402	-0.3631
FRC	4.6070	0.6932	4.6025	1.1031	-4.3799	-0.9049	-4.2992	-1.6081	0.6528	-0.1152	0.6905	-0.3923
FC	3.1817	0.3529	3.0568	0.7387	-3.0365	-0.6370	-2.8737	-1.1670	0.4400	-0.8510	0.4456	-0.3831
BF	2.4651	0.3151	2.6056	0.5792	-2.6654	-0.8866	-2.9459	-1.3992	0.0773	-0.5234	-0.0843	-0.7684
RMGIC	2.1849	0.2641	2.3088	0.5447	-2.2272	-0.7041	-2.4445	-1.1277	0.1968	-0.4043	0.0825	-0.5497

(MOD-US: MOD cavity upper surface, MOD-LS: MOD cavity lower surface, MO-US: MO cavity upper surface, MO-LS: MO cavity lower surface)

On the upper surface of the base materials, the lowest tensile stress values were observed in the BF models and on the MOD and MO cavities' lower surfaces of the base materials, the lowest values were observed in the FC and BF models, respectively (Table 3).

DISCUSSION

A number of studies have been conducted that investigated the effects of cavity design and restorative material on stress distribution in tooth structures and restorative materials.[3,8,16] The results obtained from these studies are confusing and contradicting. To clarify this issue, a 3D FEA of stresses associated with the MO and MOD cavity designs and different base materials in endodontically treated molars was performed in this study.

During mastication, teeth are subjected to forces that vary magnitudes and directions. Because of stresses and strains occurred on the teeth and restorative materials caused by these chewing forces, the fracture resistance of teeth and restoration structures decrease.[19] Intraoral loads vary between the range from 10N-431N.[18] In addition to this, a number of studies showed that oblique loads create more stress than vertical loads.[2,20,21] In the current study, an oblique loading of 240N was applied to the central fossa, distal marginal ridge, mesiobuccal cusp tip, and distobuccal cusp tip to mimic the forces applied to the mandibular first molar during the closing phase of mastication.[18]

Apart from chewing forces, the cavity design and the restorative procedure has been described to affect stress and strain produced in restored teeth. A lot of studies have been analyzed the biophysical stress and strain in restored teeth and they have shown that restorative procedures can make tooth more vulnerable to fracture and teeth should be strengthened by choosing the appropriate restorative material.[22–24]

According to the 3D FEA results performed in the current study, the von Mises stress areas were concentrated on the points that oblique forces were applied. Regarding the stress occurred on enamel, high stress areas were concentrated on distobuccal cusp, and cervical area, which was the neighboring area to the cortical bone for both cavity type (Figure 4). It was thought that similar stress distributions on enamel were occurred because of the same final restorative material (resin composite) used for all models. Since the elastic modulus of base materials were different, stress distribution differences were observed in the area between mesiolingual and distolingual cusps. It was observed that when the elastic modulus of the base material reduced, the stress occurred in that area increased.

Regarding the von Mises stresses that occurred in the final restorative material, high stress areas were concentrated on the lower surface and neighboring area to the gingival walls of the restoration (Figure 5). As the elastic modulus of base materials reduced, the high stress areas occurred on the neighboring area to the gingival wall increased. If high stress areas become more concentrated, cracks and fractures could be seen on the gingival wall of the cavity and restoration. As a result of this situation microleakage and secondary carries, and eventually failure of the restoration might occur.

Recently a few studies suggested that restorative materials with low elastic modulus could be used as stress barrier on gingival wall of the cavity. According to the results of current study, as the elastic modulus of base materials reduced, high stresses on the neighboring area to the gingival wall became more concentrated. In these high stress areas, restorative materials with low elastic modulus would be vulnerable to deformation and then this would result with the failure of the restoration. Further investigations are needed to evaluate stress distributions on the neighboring area to the gingival walls of restorations.

Regarding the stresses that occurred in dentin, the highest von Mises, compressive and tensile stress values were obtained in RMGIC, BF, and FC models. The lowest stress values were obtained in CR models. It might be the reason of this result depended on the elastic modulus of base materials. The elastic modulus of RMGIC, BF and FC were lower than other base materials, and CR had the highest elastic modulus.

When differences in cavity type was considered, high stress areas found to be concentrated on gingival walls of both cavities. Because of that, compressive and tensile stress values obtained from the selected points on gingival walls and the effect of base materials on the stress distribution was evaluated according to these selected points. Considering selected points on dentine in MOD cavity design (distal gingival wall, mesial gingival wall), the highest von Mises, compressive and tensile stress values observed on distal gingival walls of the cavity. The chewing force applied on distal marginal ridge might be the reason of this situation. Regarding the base material type, the highest stress values observed in RMGIC, BF and FC models. Stresses occurred in gingival walls considered to be important regarding longevity of the final restoration because the cracks and fractures occurred in this area may lead to microleakage and secondary caries. Some investigators have reported that cracks, fractures and microleakage occurred in class II cavities appeared to be major clinical problem.[25–29]

When selected points on MO and MOD cavity designs were compared, it is observed that the von Mises and compressive stresses were higher in MOD cavity design and the tensile stresses were similar for both cavity design. After endodontic treatment, it is noted that the amount of stress that occurred in endodontically treated teeth might increase and the fracture resistance tend to decrease because of dental hard tissue loss.[6] Eraslan *et al*.[17] compared different cavity designs to compare stress distributions occurred on dental hard tissues and reported that lowest stress values observed in teeth with less hard tissue loss and these results are compatible with the current study.

After oblique forces that applied to the models with MOD and MO cavity designs, it is observed that high stress areas were concentrated on the upper surface of base materials (Figure 7). For this reason, two different points -upper and lower surfaces of base material- were selected to evaluate stress distributions on base materials.

These selected points were determined so that they centered on the upper and lower surfaces of the base materials. Regarding stresses occurred on these points, the highest von Mises and compressive stress values were observed in CR models and the lowest values observed in RMGIC models. CR had the highest elastic modulus among all tested materials hence it absorbed the stresses and didn't transmit to the dental hard tissues, vice versa for RMGIC. The stress values that occurred on the lower surface of the base materials were lower than that occurred on the upper surface. The values that occurred on the lower surface were similar regarding the type of base material because the stresses might not be transmitted to the lower surface of base materials.

When tensile stress values were evaluated for both cavity designs, the highest values were obtained in CR models and the lowest values were obtained in BF models on the upper surface of the base materials. Although BF material doesn't have the lowest elastic modulus among all materials, it has the highest Poisson's Ratio and this might be reason of the difference in stress distributions.

Among the materials tested in the current study, FRC is a new material which have developed more recently and there are not so many studies available in the literature that evaluated the stresses occurred in teeth restored with FRC. The elastic modulus and poisson ratio of FRC obtained from the manufacturer and the material was presumed to be isotropic. Regarding the results of the study, FRC and GIC might be best choices to restore endodontically treated teeth because their elastic modulus is similar to elastic modulus of dentin. Also, FRC reduces high stress values and prevents the crack formation on composite/ adhesive resin interface because this material contains fiber particles.[29] Additionally, the fluor releasing mechanism of GIC might be beneficial because of anticariogenic effect.

CONCLUSIONS

Within the limitations of the current study, it might be concluded as;

- Regarding the effect of base material, materials with elastic moduli similar to dentin; FRC and GIC, may be better choice to avoid high stresses within the tooth and restoration.
- Regarding the effect of cavity design, MO cavity design caused low stress values on tooth structures than MOD cavity.

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CONFLICTS OF INTEREST

None

Farklı Kaide Materyallerinin Kanal Tedavili Dişlerdeki Stres Dağılımı Üzerine Etkileri: 3B SEA

ÖZ

Amaç: *Bu çalışmada diş sert dokularında, kaide materyalinde ve restorasyonda oblik kuvvetlerin oluşturduğu stres dağılımları, farklı kaide materyalleri ve direkt kompozit restorasyonla restore edilen endodontik tedavili daimî mandibular ilk molar dişlerde 3B-SEA metodu ile değerlendirildi.* ***Gereç ve Yöntemler:*** *İki farklı restoratif yaklaşım için; MO kavite tasarımı ve MOD kavite tasarımı oluşturuldu. Sonra kök kanal tedavisi modellenmiştir. Kompozit rezin (CR), geleneksel cam iyonomer siman (GIC), fiberle güçlendirilmiş kompozit rezin (FRC), rezin modifiye cam iyonomer siman (RMGIC), akışkan kompozit (FC) ve Bulk-Fill kompozit rezin (BF) kaide olarak kullanılmıştır. Von Mises, basınç ve çekme stresleri; mine, dentin, kaide materyalleri ve nihai restorasyonda sonlu elemanlar stres analizi yöntemi kullanılarak analiz edildi.* ***Bulgular:*** *Ortaya çıkan stresler ile ilgili olarak; mine, kaide materyali ve nihai restorasyonda CR en yüksek streslere ve RMGIC en düşük streslere neden olmuştur. Dentinde, RMGIC en yüksek strese ve CR en düşük strese neden oldu. MOD kavite tasarımının, analiz edilen tüm materyaller için MO kavite tasarımından daha fazla strese neden olduğu not edildi.* ***Sonuçlar:*** *Dentine yakın elastik modülüsü olan materyaller; FRCR ve GIC, diş ve restorasyonda yüksek streslerden kaçınmak için daha iyi bir seçenek olabilir.* ***Anahtar Kelimeler:*** *Kompozit rezin, cam iyonomer simanlar, fiberle güçlendirilmiş kompozit, sonlu eleman analizi.*

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