10.5005/jp-journals-10024-1677

ORIGINAL RESEARCH

Finite Element Analysis of the Endodontically-treated Maxillary Premolars restored with Composite Resin along with Glass Fiber Insertion in Various Positions

[1]Elmira Jafari Navimipour, [2]Maryam Firouzmandi, [3]Fatemeh Sadat Mirhashemi

ABSTRACT

Aim: This study evaluated the effect of three methods of glass fiber insertion on stress distribution pattern and cusp movement of the root-filled maxillary premolars using finite element method (FEM) analysis.

Materials and methods: A three-dimensional (3D) FEM model of a sound upper premolar tooth and four models of root-filled upper premolars with mesiocclusodistal (MOD) cavities were molded and restored with: (1) Composite resin only (NF); (2) Composite resin along with a ribbon of glass fiber placed in the occlusal third (OF); (3) Composite resin along with a ribbon of glass fiber placed circumferentially in the cervical third (CF), and (4) Composite resin along with occlusal and circumferential fibers (OCF). A static vertical load was applied to calculate the stress distributions. Structural analysis program by Solidworks were used for FEM analysis. Von-Mises stress values and cusp movements induced by occlusal loading were evaluated.

Results: Maximum Von-Mises stress of enamel occurred in sound tooth, followed by NF, CF, OF and OCF. Maximum Von-Mises stress of dentin occurred in sound tooth, followed by OF, OCF, CF and NF. Stress distribution patterns of OF and OCF were similar. Maximum overall stress values were concentrated in NF. Although stress distribution patterns of NF and CF were found as similar, CF showed lower stress values. Palatal cusp movement was more than buccal cusp in all of the models.

Conclusion: The results of our study indicated that while the circumferential fiber had little effect on overall stress concentration, it provided a more favorable stress distribution pattern in cervical region. The occlusal fiber reduced the average stress in the entire structure but did not reduce cuspal movement.

Clinical significance: Incorporating glass fiber in composite restorations may alter the stress state within the structure depending on fiber position.

Keywords: Endodontically-treated premolars, Fiber reinforced composite resin, Finite element analysis, Stress distribution.

How to cite this article: Navimipour EJ, Firouzmandi M, Mirhashemi FS. Finite Element Analysis of the Endodontically-treated Maxillary Premolars restored with Composite Resin along with Glass Fiber Insertion in Various Positions. J Contemp Dent Pract 2015;16(4):284-290.

Source of support: This project was carried out by the financial support from the deputy dean of research at Tabriz University of Medical Sciences.

Conflict of interest: None

[1]Department of Operative Dentistry, Tabriz University of Medical Sciences, Tabriz, Iran

[2]Department of Operative Dentistry, Shiraz University of Medical Sciences, Fars, Iran

[3]Department of Mechanics of Agricultural Engineering Ferdowsi University of Mashhad, Mashhad, Iran

Corresponding Author: Maryam Firouzmandi, Assistant Professor, Department of Operative Dentistry, Shiraz University of Medical Sciences, Fars, Iran, Phone: 00987116263193 e-mail: firouzmandi@sums.ac.ir

INTRODUCTION

After endodontic treatment, the teeth are more prone to fracture. The main reason is the loss of the dental tissue due to previous caries and endodontic access preparation.[1-3] Despite the extensive studies on the root-filled teeth, the optimal treatment planning for the final restoration of the endodontically-treated posterior teeth remains controversial.[1]

With the development of adhesive techniques, composite resin is being vastly used as the restorative material for the restoration of the endodontically-treated teeth. Adhesive restorative materials enhance structural continuity between buccal and lingual cusps and decrease deflection of cusps under occlusal load.[4-6] The other advantage of adhesive systems is that if adequate substrates for bonding are present, then the mechanical retention features will not be as crucial. This would eliminate the need for placement of a post which would be risky especially for the delicate roots of the upper premolars.[7] Resin composites have some shortcomings when used as a direct restorative material for the large stress-bearing areas; which is due to polymerization shrinkage effect and limitations in mechanical properties.[8] Composites that are reinforced with fiber (fiber-reinforced composite or FRC) are shown to better overcome the mechanical limitations.[9, 10] Owning to the satisfactory resilience and resistance properties, FRCs enable the load transfer to the dental structures more physiologically, thus preventing the development of detrimental stresses.[11] The mechanical behavior of FRC restorations in the structurally compromised teeth has been investigated in some studies using fracture strength tests.[12-15] One of the contributing factors to the strengthening effects of fibers seems to be the fiber position. If the position of fibers inside the restoration is more occlusal they will be more fracture resistant.[13,16,17]

A set of events precedes the ultimate fracture of the structures: Loading the tooth-restoration complex generates internal stresses, and then the stresses promote the microcrack propagation. Initial microcracks might weaken the structure of the material, resulting in its failure.[18] *In vitro* fracture resistance tests only measure the endpoint in the failure process. Identification of internal stress maps may provide useful information about the sites which are more prone to failure initiation. Such a determination of internal stresses can be accomplished with the appropriate finite element analysis.

Several studies have used the non-destructive finite element method (FEM) along with the destructive mechanical tests.[19-21] In most cases FEM was a step forward in understanding the mechanism of failure.[19,20] Finite element methods results were consistent with the load test results in cusp replacing composite restorations[19] and FE analysis predicted adhesive failures of the restorations that had been observed in a load test.[19] In the endodontically-treated premolars restored with composite resins, restoration and endodontic treatment increased the incidence of unfavorable fractures which were correlated with the FEM results.[20] Exploring the biomechanical behavior of endodontically-treated premolars showed that reduced fracture resistance was accompanied with higher stress concentrations.[21] This study was designed to test the null hypothesis that composite resin restoration accompanied with variable positioning of glass fibers does not affect stress distribution patterns and buccal and palatal cusp movements by means of three-dimensional (3D) FE analysis in endodontically-treated maxillary premolars.

MATERIALS AND METHODS

A maxillary premolar which was considered to be the representative of the typical outer morphology was selected. The tooth was extracted for routine clinical purposes. The 3D optical digitizing system ATOS II (GOM, Braunschweig, Germany) was used to digitize the external surface of the tooth with high accuracy. The measured data that usually are in the form of point clouds were imported to Solid-Works 2010 environment (Solidworks Crop, Concord, MA, USA) to construct the 3D solid tooth. Next the solid model of the internal anatomy of the tooth, e.g. enamel thickness and pulp system, was generated. Following the completion of the solid model of intact premolar tooth, the alternative four models [no fiber (NF), occlusal fiber (OF), circumferential fiber (CF), and dual fiber (OCF)] with the endodontically-treated root canals and mesiocclusodistal (MOD) cavities (2.5 mm remaining buccal and lingual wall thickness in the height of contour of each surface and the gingival cavosurface margin 1.5 mm coronal to the CEJ) were constructed. The MOD cavities in the aforementioned four models were filled with four identical restorative modalities as described in our previous study.[16] In brief, NF model restored with composite resin without fiber reinforcement. In OF model after filling the cavity with composite resin, a groove measuring 2 mm in width and 1 mm in depth was created buccolingually on the cusp tips, a ribbon of fiber 2 mm in width and 0.2 mm in thickness with 0.1 mm thick flowable composite resin base was adapted into the groove. The exposed fiber surface was also filled with composite resin. In CF model tooth restoration was began by placing 1 ± 0.5 mm thick composite resin in mesial and distal aspects to reconstruct proximal surfaces. Then the fiber was adopted inside the cavity walls in a circumferential manner using 0.1 mm thick flowable composite resin; the rest of the cavity was filled with composite resin. Occlusal and CF were incorporated in the restoration of dual fiber model using the above mentioned protocols.

Each of these five models with their PDLs was assembled on the maxillary bone. The analysis was performed by a 3D FE analysis software package (ABAQUS V6.9-3; Simulia Corp, Providence, USA). Materials used in the study were considered to be isotropic, homogeneous and linearly elastic. The elastic properties were adopted from the literature and are described in Table 1.[22-25]

The nodes at the mesial and distal surfaces of the bone were fixed in all directions, as the boundary condition. Connectivity between all parts of the models was assumed to simulate 100% osseointegration. Models were meshed with four-node tetrahedral solid elements.

Table 1: Mechanical properties of materials[22-25]

Materials	*Young's modulus (GPa)*	*Poisson's ratio*
Cortical bone	13.7	0.30
Cancellous bone	1.37	0.30
Dentin	24	0.33
Enamel	87.7	0.33
Periodontal ligament	0.0000689	0.45
Gutta-percha	0.14	0.45
Composite	24.5	0.31
Flowable composite	13.5	0.39
Fiber	33.1	0.22

A 300-N static vertical occlusal load was applied through the contact of a 5 mm diameter round bar on the cusps' slopes to calculate the stress distribution.

RESULTS

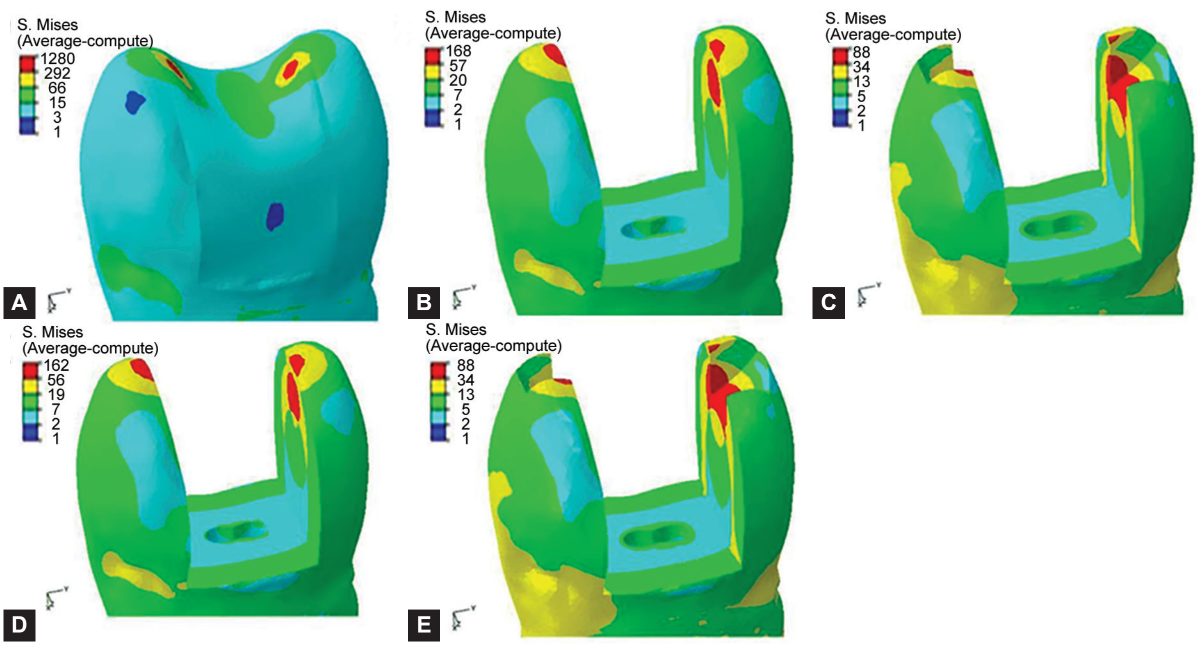
Figures 1A to E show Von-Mises equivalent stress for the five models. Stress distribution patterns of NF and CF were found as similar but CF showed lower stress values. Occlusal fiber and OCF showed the lowest stress concentration. Total cusp displacement of the models is presented in Figures 2A to E. Palatal cusp movement was more than buccal cusp in all of the models. Occlusal fiber and OCF showed higher amount of cusp movement. Maximum Von-Mises stress values and maximum cusp displacements in the structures are summarized in Table 2. Maximum Von-Mises stress of enamel occurred in sound tooth, followed by NF, CF, OF and OCF. Maximum Von-Mises stress of dentin occurred in sound tooth, followed by OF, OCF, CF and NF. For a more comprehensive stress evaluation near the occlusal and CF two paths were defined. In the Figure 3, the path traces are indicated with two yellow circular points. Both of the paths are perpendicular to the interface between composite and natural tooth; one path is a little above the cavity floor adjacent to the CF, and the other one is just under the OF. Von Mises stress was evaluated along these paths (Figs 4 and 5). Two other paths, extending along the buccal and palatal cusp from CEJ to the cusp tips were defined (Fig. 3). Along these paths, displacements perpendicular to the tooth axis were determined. Figure 6 shows the buccal and palatal cusp displacements.

DISCUSSION

The null hypothesis that glass fiber position in the composite restoration does not affect the stress distribution and buccal and palatal cusps movements was rejected in this study. Since stress analysis in a restored tooth is very complicated, 3D-FEM was used in this study. The numerical model used in FEM helped in standardization of the various study groups and eliminating the effect of diversity in natural tooth samples.

The loading condition was set based on the previous fracture resistance test in which the load was applied using a round bar with two contact points on buccal and palatal cusps.[16] Although the amount of load only affects the calculated stresses and not the ratio of different stresses, the magnitude of the load was selected to be approximately equal to the normal biting force in the maxillary premolar region.[26]

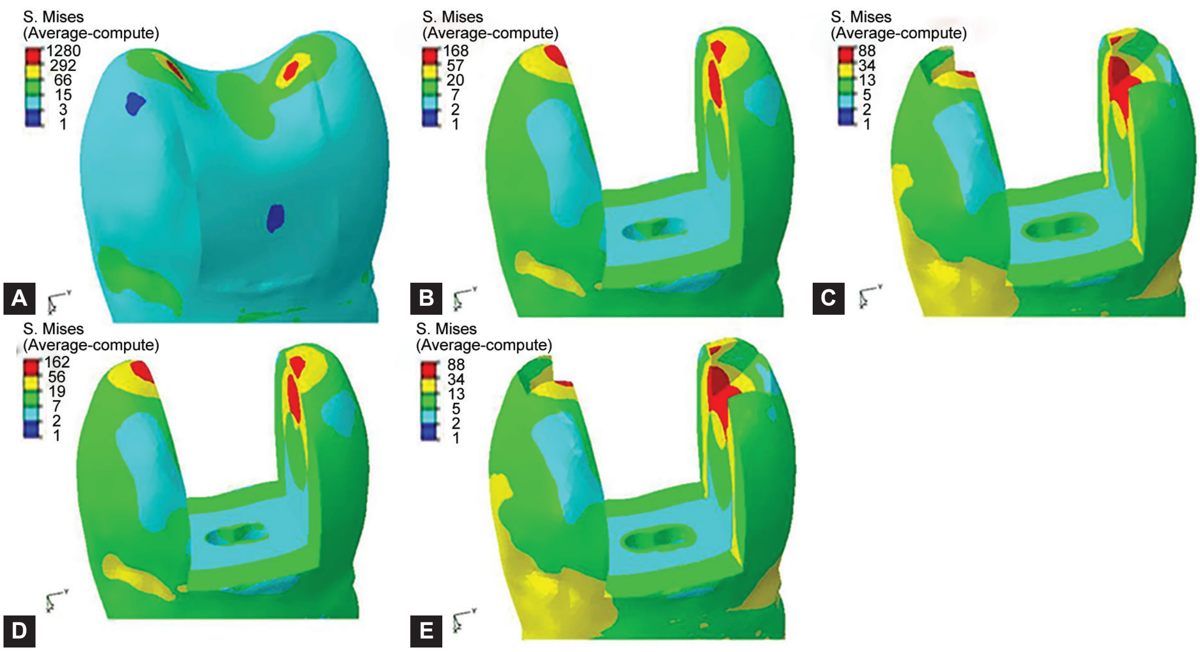
An ideal restoration is expected to induce a stress pattern similar to the sound tooth; therefore, in the present study the stress distribution patterns of the study models were compared to a sound tooth model. The



Figs 1A to E: Von-Mises stress distribution due to vertical loading in: (A) Sound tooth, (B) No fiber model, (C) Occlusal fiber model, (D) Circumferential fiber model and (E) Dual fiber model

Table 2: Maximum stresses (MPa) and cusp displacements (µm)

	Sound tooth	*No fiber model (NF)*	*Occlusal fiber model (OF)*	*Circumferential fiber model (CF)*	*Dual fiber model (OCF)*
Maximum Von-Mises stress within enamel	1280	168	88.1	161.8	87.81
Maximum Von-Mises stress within dentin	32.4	22.1	28.7	23.6	28.61
Maximum displacement of enamel	4.4	1.9	1.9	1.9	1.51
Maximum displacement of dentin	0.74	1.9	1.9	1.1	1.1
Maximum displacement of composite	—	14.5	12.29	13.80	13.37



Figs 2A to E: Cuspal displacement due to vertical loading in: (A) Sound tooth, (B) No fiber model, (C) Occlusal fiber model, (D) Circumferential fiber model and (E) Dual fiber model

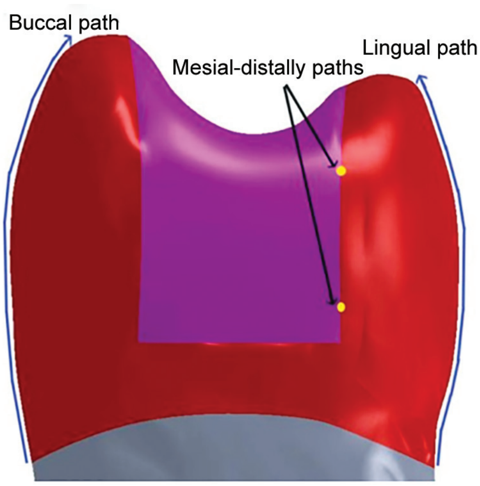
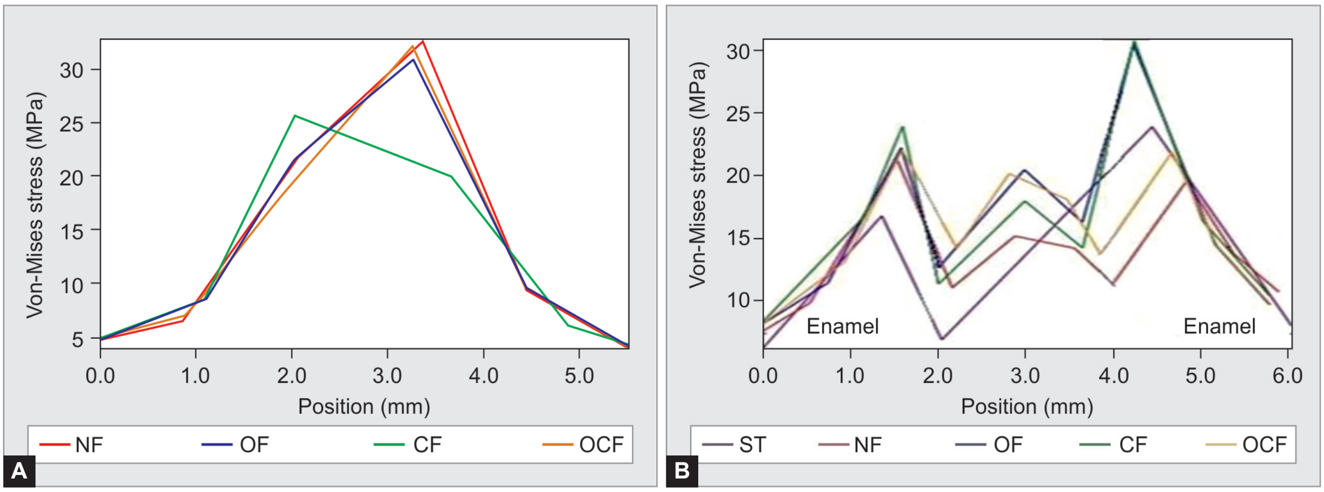


Fig. 3: Paths defined in the tooth

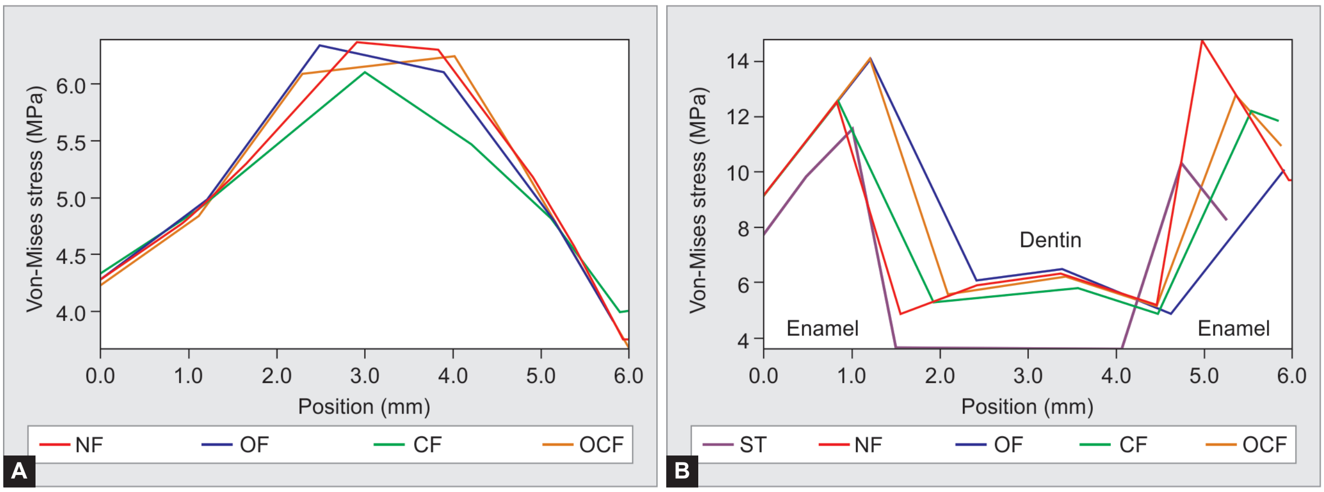
highest Von-Mises stress value for enamel and dentin was observed in the sound tooth which was related to the load application points. This was in accordance with previous studies.[22,27] In the sound tooth, the load was applied directly on enamel and then was transferred to the underlying dentin but in the restored tooth the load application points were on the composite.

Among the restored models higher stress values of enamel were observed in no fiber and CF models; while the maximum Von Mises stresses of dentin were recorded in OF and dual fiber models. This could be explained by the load application points. In NF and CF models the applied load was transferred to the composite in the cavity side and to the enamel in the tooth side, but in OF and dual fiber models, due to presence of an occlusal slot filled by fiber ribbon and composite, the load was applied on the restoration and was transferred to the underlying dentin. Notwithstanding the high stress areas on occlusal enamel, the overall stress value in the sound tooth was the lowest. As reported previously MOD preparation and root canal treatment accentuates stress concentration within the dental structures, mainly due to the loss of tooth tissue.[20]

Stress distribution patterns in NF and CF models were almost similar. In a previous study when composite resin alone or composite resin along with the CF were used for restoring lower premolars similar stress distribution characteristics were obtained.[22] In CF model, the stress value in most of the areas was at least 1 MPa lower than



Figs 4A and B: Von-Mises stress path little below the occlusal fiber: (A) On the composite side, (B) On the natural tooth side (ST: sound tooth; NF: No fiber model; OF: Occlusal fiber model; CF: Circumferential fiber model; OCF: Dual fiber model)



Figs 5A and B: Von-Mises stress path little above the cavity floor: (A) On the composite side, (B) On the natural tooth side (ST: sound tooth; NF: No fiber model; OF: Occlusal fiber model; CF: Circumferential fiber model; OCF: Dual fiber model)

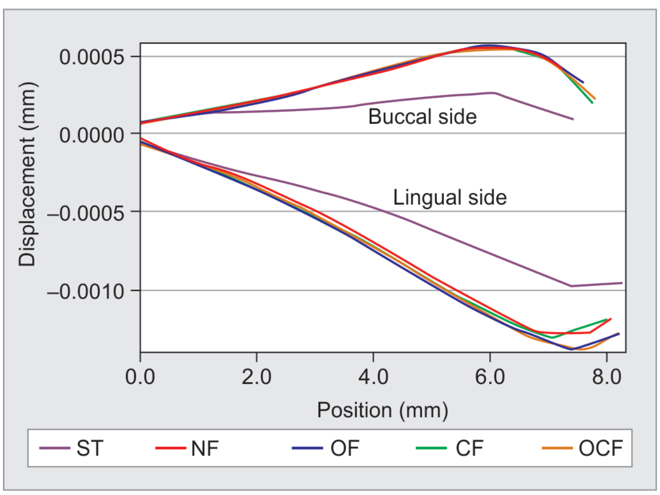


Fig. 6: Buccal and palatal cusp displacements path (ST: sound tooth; NF: No fiber model; OF: Occlusal fiber model; CF: Circumferential fiber model; OCF: Dual fiber model)

the corresponding areas in NF model. In agreement with this finding in our previous study, fracture strength of CF group was higher than NF group.[16] Failure probability of a structure is a function of the stress state and strength properties of the materials.[19] Incorporating fiber into composite restoration increases flexure strength of the composite,[28] which might help improving the fracture resistance of the FRC restored teeth.

Occlusal fiber and dual fiber models showed the same stress distribution patterns, and the stress value in these two models were lower than NF and CF models. This is in accordance with the higher fracture resistance recorded for OF and dual fiber groups in our previous study.[16] Placing fibers in the occlusal third of the cavities, significantly increased fracture resistance as shown in some studies.[13,17] It might be said that CF has little effect on the stress amount and distribution pattern. This is also true about the fracture strength. It has been proposed that fiber position, orientation and geometry within a structure can influence the strength properties.[29]

Stress was accumulated in the cervical region of occlusal and dual fiber models. Despite the similar stress scheme of NF and CF models in the cervical region, the amount of stress was lower in CF model, so, the most favorable stress distribution pattern among the restored models belongs to the CF model. Stress value in dentin along the gingival path in CF model was lower compared to other models. Stress value through the occlusal and gingival path in the restoration side was lower in CF model and the shape of the curve was different compared with other models. The occlusal path curve shows a peak of stress in the composite for the three models but in the CF model, the stress in the composite decreased slightly. Considering the results, CF might reduce stress value in the composite of occlusal region by splinting four walls of the cavity in the gingival region. Along the gingival path, the shape of the curves was reversed but the curve for the CF model had a peak which was still at the lower stress level. The low percentage of the unfavorable fracture mode which was observed in the previous fracture resistance study[16] can be attributed to the aforementioned different stress curves and lower stress accumulation in the cervical region of CF model.

As shown by Figure 6, movement in the palatal cusp was greater than the buccal cusp which was true for all models. This finding was confirmed by another study[27] and can be attributed to the cusps' incline and shape. Sound tooth exhibits lower cusp deflection due to homogeneity and intact structure.

There was no difference in buccal cusp movement among the models but palatal cusp movement closer to the cusp's tip was higher in OF and dual fiber models. It is hypothesized that rigidity of occlusal portion of the restoration in these models inhibits deformation of the restoration under occlusal loading and that is transferred to a higher deformation of palatal cusp.

Comparing the results of our previous fracture strength study[16] with the present stress distribution patterns, it may be concluded that despite the better fracture resistance observed in OF and dual fiber models, higher interfacial stresses and cusp movements may expose the teeth analyzed in these models to higher risk of failure; especially when the oral biologic conditions, such as repetitive masticatory loads and fatigue phenomenon are taken into the account. Higher stress concentrations in cervical region in OF and dual fiber models were in accordance with the more unfavorable fracture patterns for the corresponding groups in that study.[16] Stress accumulation in the cervical region, however, may be due to the increased amount of cusp movement in the occlusal region. Soars et al also concluded that high stress in cervical region is related to the catastrophic fractures.[20]

It should be noted that in the present study all the materials and structures were considered to be homogenous and isotropic, so the models could not simulate the exact *in vivo* conditions. In addition, the tooth restoration joint was considered to be a perfect adhesion; however, the presence of an adhesive layer with different thickness and elastic modulus may alter the stress distribution patterns. Another limitation of this study was elimination of the composite polymerization shrinkage stresses and the effect of CF in altering these stresses.

CONCLUSION

Within the limitations of the current study, it was concluded that:

1. Circumferential fiber in the gingival third of the cavity has little effect on overall stress distribution pattern but can reduce the amount of stress to some extent and provides more favorable stress distribution pattern in the cervical region.
2. The use of OF reduces the average stress in the entire structure but the stress value in cervical region increases. It may be due to the increased cuspal movement.

CLINICAL SIGNIFICANCE

Incorporating glass fiber in composite restorations may alter the stress state within the structure depending on fiber position. Occlusal fiber reduces overall stress while accentuating cusp movement and stress concentration in cervical region. In contrast CF creates more favorable stress pattern in this area.

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