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Computer Methods in Biomechanics and Biomedical Engineering

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/gcmb20

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To cite this article: Gulhan Yildirim, Cihan Demir, Melahat Çelik Güven, Osman Koç & Evrim Eligüzeloglu Dalkiliç (2022) Influence of fiber insertion and different material type on stress distribution in endocrown restorations: a 3D-FEA study, Computer Methods in Biomechanics and Biomedical Engineering, 25:13, 1509-1519, DOI: 10.1080/10255842.2021.2019228

To link to this article: https://doi.org/10.1080/10255842.2021.2019228

Published online: 29 Dec 2021.

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COMPUTER METHODS IN BIOMECHANICS AND BIOMEDICAL ENGINEERING
2022, VOL. 25, NO. 13, 1509–1519
https://doi.org/10.1080/10255842.2021.2019228

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Influence of fiber insertion and different material type on stress distribution in endocrown restorations: a 3D-FEA study

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ABSTRACT

The study aimed to evaluate the effects of fibers insertion and restorative material type on the stress distribution in endocrowns with finite element analysis. Five 3D models of first mandibular molars were created and restored as follows: (1) IN: intact tooth, (2) IPS-E: tooth restored with lithium disilicat ceramic endocrowns, (3) C-E: tooth restored with composite endocrowns, (4) IPS-E + F: lithium disilicate ceramic endocrowns + fiber, (5) C-E + F: composite endocrowns + fiber. Vertical masticatory load was imitated with finite element analysis. The equivalent stress of von Mises failure criterion (mvM) was calculated. The maximum mvM stress, enamel/crown, dentin and cement were compared among models and strength of the materials. Endocrowns presented a lower mvM stress level than intact tooth. In IPS-E, the mvM stress values in the crown and dentin were higher than C-E, while the mvM stress values in cement were higher in C-E group. Fibers insertion did not affect the stress level of IPS-E and C-E groups. In IPS model, fiber showed more stress absorption than C-E. The restorative material type changed the stress distribution of endocrown restorations. The fiber application did not affect the stress distribution in either endocrown group. But, more stress absorption was observed in fiber under IPS-E than C-E.

ARTICLE HISTORY
Received 15 August 2021
Accepted 13 December 2021

KEYWORDS
Finite element analysis; stress; endocrown; lithium disilicat; composite

Introduction

Restoration of endodontically-treated teeth (ETT) is a very common problem in restorative dentistry due to the high risks associated with biomechanical failure (Yeh 1997; Ferrari et al. 2000). The loss of dental tissue related to caries, excessive cavity preparation and physical changes and/or dehydration in the dentin tissues are important causes of reduced fracture resistance and ETT stiffness (Reeh et al. 1989; Papa et al. 1994; Mormann et al. 1998). To prevent the cracking of ETT and the risk of tooth fracture, the most suitable cavity design and the best material combination should be chosen by the dentist, in order to provide maximum tooth function and appearance (Lin et al. 2008; Chang et al. 2009).

With the development of adhesive dentistry and the emergence of reinforced-ceramic materials, the restoration of teeth with large coronal tissue loss is possible thanks to cuspal coverage restorations (Govare and Contrepois 2020). One of these restorations is endocrowns and defined as "bonded overlay restorations" which anchor to the internal portion of the pulp chamber (Rocca et al. 2013). They are considered comparatively easy and low-cost procedures, and are usually recommended for use in molars (Dejak and Młotkowski 2013). Compared to post-core retained crowns, endocrowns do not require root dentin removal for the retainer and prevent the risk of recontamination during disobturation (da Cunha et al. 2017).

Recent studies have shown different dental materials can be used in the endocrown restoration production, such as resin composite, nanoceramic resin, lithium disilicate ceramic (Biacchi and Basting 2012), zirconia-reinforced lithium silicate and both hybrid and feldspathic ceramics (Rocca et al. 2013; da Cunha et al. 2017; Zarone et al. 2019). The choice of the restoraion material is an important factor that can influence the survival rate of endocrowns (Tribst et al. 2021). Previous study results have shown adhesive failure and unfavorable fractures observed in ceramic-based materials, while a more positive mechanical behavior was observed in resin-based composite restorations (Magne and Knezevic 2009; Magne et al.

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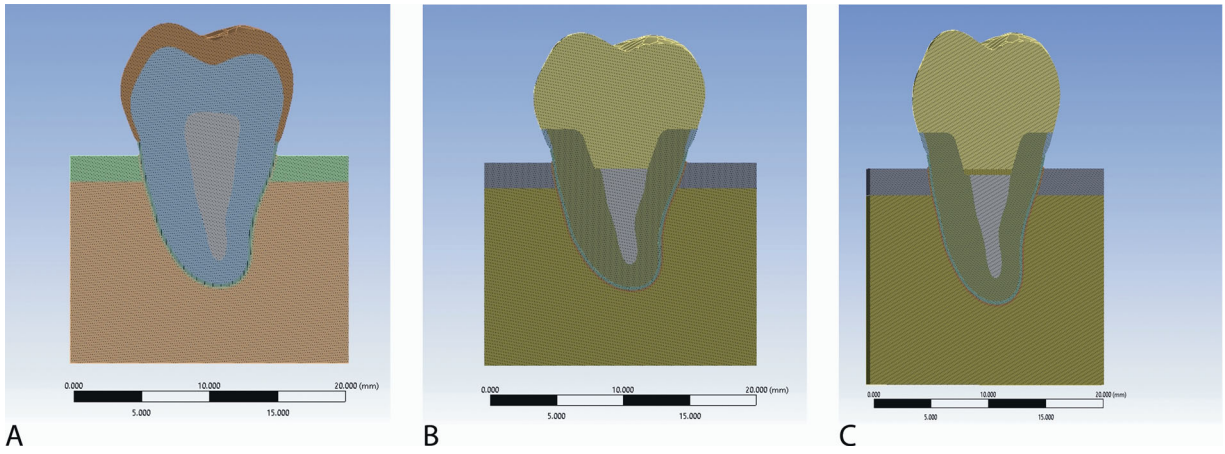


Figure 1. (a) Schematic illustration of the intact teeth; (b) Schematic illustration of the endocrown groups; (c) Schematic illustration of the endocrown + fiber groups.

2014; El-Damanhoury et al. 2015; Bankoğlu Güngör et al. 2017; Pedrollo Lise et al. 2017).

Recent advances in restorative dental material properties and fibers used with composites have encouraged clinicians to apply adhesive restorations on ETT (Hshad et al. 2018; Mena-Álvarez et al. 2020). In particular, fibers have further improved the properties of composite restorations (Dalkılıç et al. 2019). Ribbond (Ribbond, Seattle, WA, USA) is a polyethylene fiber with an ultra-high elastic modulus. These fibers have superior physical properties, such as increasing the flexural properties of the composite resin, having an elastic modulus similar to dentin, providing better levels of fatigue resistance, and effective force transmission (Eskitascıoglu et al. 2002). Previous studies have shown that polyethylene fiber has a stress altering effect and inserting fiber under the composite restorations increased the fracture strength of endodontically treated teeth (Rudo and Karbhari 1999; Belli et al. 2006; Sengun et al. 2008). While the mechanical properties of endocrowns produced from different materials have been evaluated in previous studies, there is no in vitro study evaluating the effect of application of fibers underneath the endocrown restorations (Biacchi and Basting 2012; Rocca et al. 2016). There is one case study in the literature in which glass fibers were used under endocrown restorations (Rocca et al. 2013).

To investigate the stress distribution caused by vertical occlusal load in adhesively restorated endodontically treated teeth, finite element analysis (FEA) is often used (Eraslan et al. 2011; Gloria et al. 2018; Ausiello et al. 2020). FEA is an engineering tool to understand the material's structural processes and provides information on cavity design and restorative material rigidity influence of the restored teeth (Toparli et al. 1999; Yamanel et al. 2009). This analysis is based on the numerical method and is able to determine stress concentration area regions that might have failure (Zhu et al. 2017). Mechanical behavior of various material combinations can be evaluated using this method and it allows for simulation of clinical applications without using in vitro human teeth and/or to test in vivo on the patients (Oliveira et al. 2014; Ausiello et al. 2019).

The aim of the present study was to evaluate the effect of fiber insertion and restorative material type on stress distribution in ETT mandibular human molars restored with endocrown by means of FEA. The null hypothesis included two corollaries: (1) fiber insertion would not effect the stress distribution of endodontically treated mandibular molar teeth restored with endocrown and (2) the type of restorative material would not effect stress distribution.

Material and methods

Generation of the geometric model

A three-dimensional (3D) model of a mandibular first molar tooth was digitized with a micro-CT (Computed Tomography) scanner system (InEos X5, Sirona Dental Systems GmbH, Bensheim, Germany). This blue light lab scanner is accredited to be accurate within 2.1 microns (ISO 12836) (Etemad-Shahidi et al. 2020). The sample size was determined by using a sample size calculation with 95% confidence level and a margin of error of 5%. This has been confirmed by previous studies as acceptable to achieve statistically significant results (Mangano et al. 2017; Kang et al. 2020). Point clouds were obtained from these scans and were exported in stereolithography (STL) format. The file in STL format was processed in the

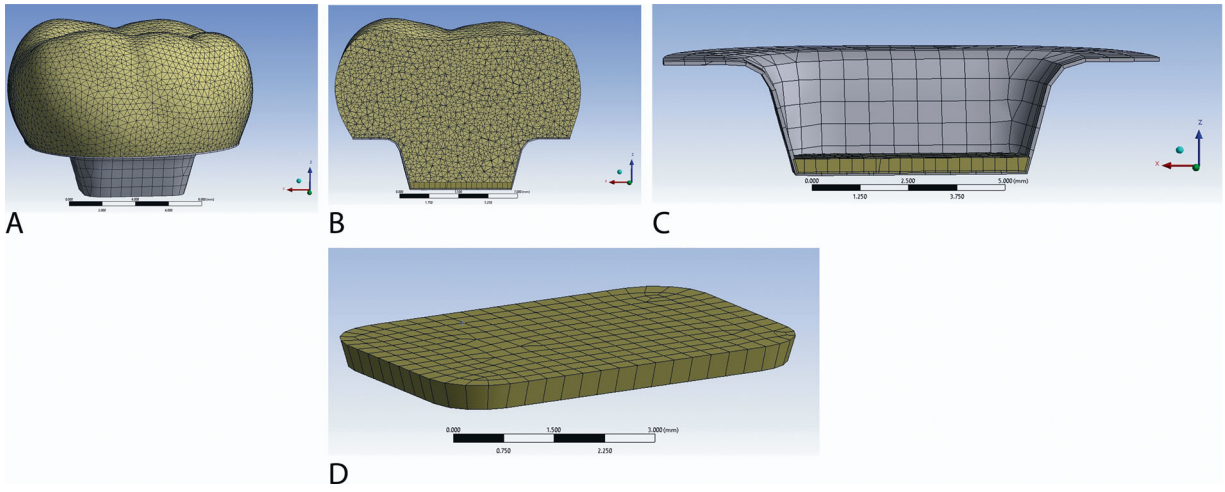


Figure 2. (a–c) Endocrown cavity design and layer of the resin cement, (d) the layer of fiber in group IPS-E + fiber and C-E + fiber.

Table 1. Element numbers, node numbers and element quality values for the models.

Model	Element quality (avarege, totally)	Element numbers	Node numbers	Element type
Model IN (intact)	0.84047	1103634	1615872	SOLID187- 3-D 10-Node
Model IPS-E (Lithium disilicat ceramic Endocrown)	0.83742	974329	1437592	SOLID187- 3-D 10-Node
Model C-E (Composite Endocrown)	0.83733	974897	1438264	SOLID187- 3-D 10-Node
Fiber + Model IPS-E (Lithium disilicat ceramic Endocrown)[a]	0.83735	967720	1427963	SOLID187- 3-D 10-Node
Fiber + Model C-E (Composite Endocrown)[a]	0.83735	967720	1427963	SOLID187- 3-D 10-Node

[a]The Solid-Shell elements and the Plane elements were used for the ribbond and the cement layer.

Spaceclaim CAD software program (SpaceClaim Corporation; Canonsburg, PA, USA). The solid tooth model and its sub-components were obtained according to the point density. The periodontal ligament (PDL) and cortical bone were simulated around the models. The FEA models were modeled with 0.2 mm thickness periodontal ligament, 0.3 mm thickness lamina dura, and the cortical and trabecular bone were generated. Cortical bone structure was constructed with a 2 mm thickness (Kraus et al. 1969).

These models were composed of the following geometries: endocrown, cement film, tooth preparation, periodontal ligament, polyethylene fiber (in some of them) and a fixation cylinder. The aim was to simulate a large coronal tissue defect with ETT with an indirect restoration (Figure 1).

Five individual FEA models were created:

- Intact (IN): a sound mandibular first molar. The crown length: 7.3 mm, occluso-cervical and bucco-lingual dimensions: 9 mm, mesial and distal root length; 13 and 12.7 mm.
- Lithium disilicate ceramic Endocrown (IPS-E)
- Composite Endocrown (C-E)
- Lithium disilicate ceramic + Fiber Endocrown (IPS-E + F)
- Composite + Fiber Endocrown (C-E + F)

In all models, a pulp chamber surface of 5 mm depth and 10° wall inclination angle with soft margins were prepared and then merged with the divided part of the crown (Figure 2(a, b)). Each cavity was designed with 2.0 mm sound tissue above the cemento-enamel junction. Endocrowns were then created by the pulp chamber extension. After that, a resin cement layer (100 µm thickness) (Ausiello et al. 2017) was formed between the prepared tooth surface and the inner surface of the crown (Figure 2(c)). All endocrown models were prepared in this manner. In the IPS-E + fiber and C-E + fiber groups, the cavities were created in the same manner as the others. A layer of polyethylene fiber embedded in the flowable composite was created on the pulp chamber. Fiber-embedded flowable composite resin thickness was set at 0.4 mm (Figure 2(d)). The structures were assumed to be isotropic, linearly elastic, and homogeneous to overcome simplification and computational difficulties (Ebrahimi 2012).

Mesh generation

This is an important FEA-associate step used to obtain estimates about complex geometries and divides the system area into a large set of finite elements, of which the quantities depend on the mesh

Table 2. The mechanical properties of the materials used in teeth models.

Materials	Modulus of elasticity (GPa)	Poisson's ratio	References
Enamel	84.1	0.33	Dejak et al. (2012)
Dentin	18.6	0.31	Dejak et al. (2012)
Periodontal ligament	0.05	0.45	Holmes et al. (1996)
Cortical bone	13.7	0.3	Lin et al. (2011)
Trabecular bone	1.37	0.3	Holmes et al. (1996)
Pulp	0.0068	0.45	Vukicevic et al. (2015)
Gutta percha	0.07	0.40	Vukicevic et al. (2015)
Composite block (Paradigm MZ100)	16.00	0.24	Dejak et al. (2012)
Ceramic block (IPS Empress)	65.00	0.10	Dejak et al. (2012)
Resin cement (Multilink Automix)	5.00	0.29	Firidinoğlu et al. (2012)
Fiber (Ribbond Triaxial) + bonding agent + tetric flow	23.600	0.32	Eskitascioglu et al. (2002)

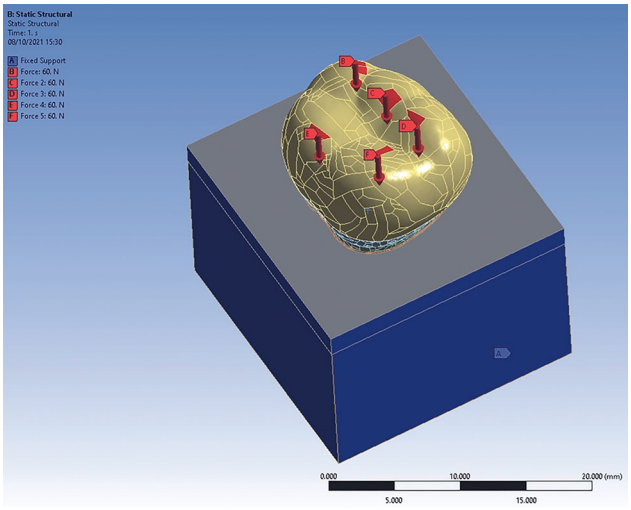


Figure 3. Boundary condition and load application points of FEA models.

structure geometry. Thus, the meshing process ensures an absolute representation of the models genuine geometries. All models were exported to the analysis software (ANSYS v11.0, Swanson Analysis, Inc., Houston, PA, USA) and meshed. The quadratic tetrahedron elements were used for solid bodies. The solid-shell and membrane element of the shell element were used for the fiber and cement, respectively, which were thin-structured layers. Element quality and structural error parameters were used together in convergence studies. The level of element quality values were kept to a minimum of 0.2 and element node numbers and quality values are presented in Table 1. Mesh density was evaluated through energy error estimation, so the discontinuous stress field is smoothed.

Boundary condition and load application

For all models, the fixation occurred at the base of the alveolar bone with fixed zero displacements and only the occlusal surface was allowed to move freely. An axial load (300 N) was applied to the occlusal surfaces at 5 contact points; three were on the outer aspects of the buccal cusps, while the other two were on the inner aspects of the lingual cusps (Figure 3) (Zhu et al. 2017) and non-separable contacts between the restoration/cement and the resin cement/tooth were considered (Fonseca et al. 2018).

Mechanical properties of materials

Mechanical properties of each material/structure used in the present study such as Young's Modulus and Poisson's Ratio (Table 2) were obtained from the literatre (Wendler et al. 2017; Ausiello et al. 2019) and the values were inserted into the analysis software.

Finite element analysis

Computer-aided mechanical software ANSYS v11.0 (Swanson Analysis, Inc., Houston, PA, USA) was used in the present study. To assess the materials' strength under complex stress conditions, the von Mises stress (vMS) tool was used as it constantly has a positive value. A qualitative stress map was created from the post-processing software using color scales in these structures, and the maximum stress value in each structure was evaluated (Tribst et al. 2018).

Results

In the present study, the maximum mvM stress value was obtained for the endocrowns (top and bottom surface), enamel/crown, dentin, cement, and fiber layer. Data were summarized via colorimetric graphs (Figures 4–8). Both the mvM and contact stress values on different surfaces were visualized using shade images to demonstrate stress distributions. The mvM stress levels in endocrowns, enamel/crown, dentin, cement, and Ribbond among different restorations were calculated (Table 3).

Model IN: For the intact molar with no restoration, the highest mvM stress value in enamel was concentrated around the central groove and reached

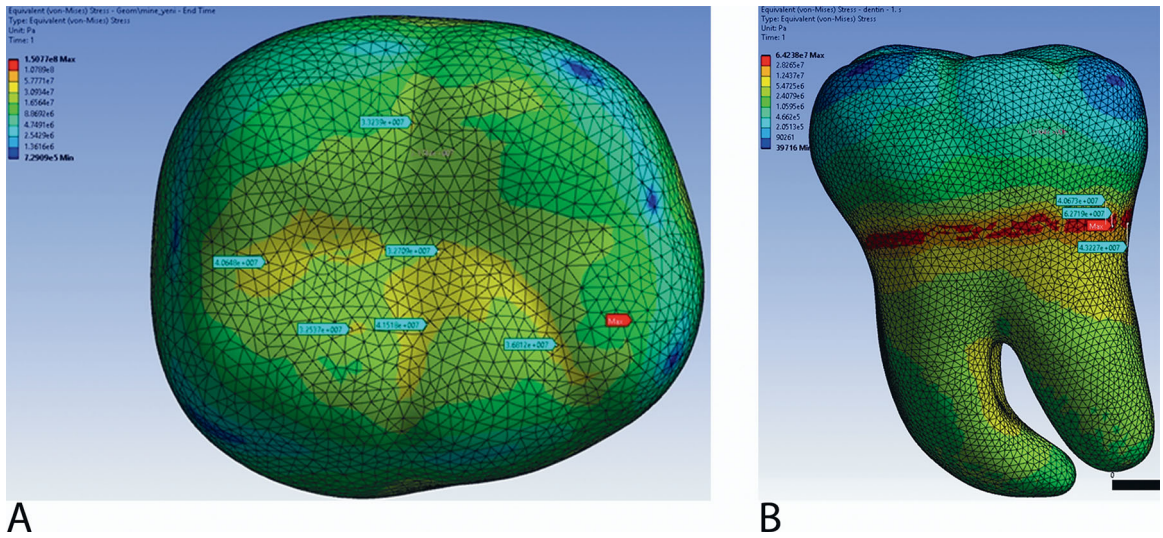


Figure 4. Stress distribution of Model IN.

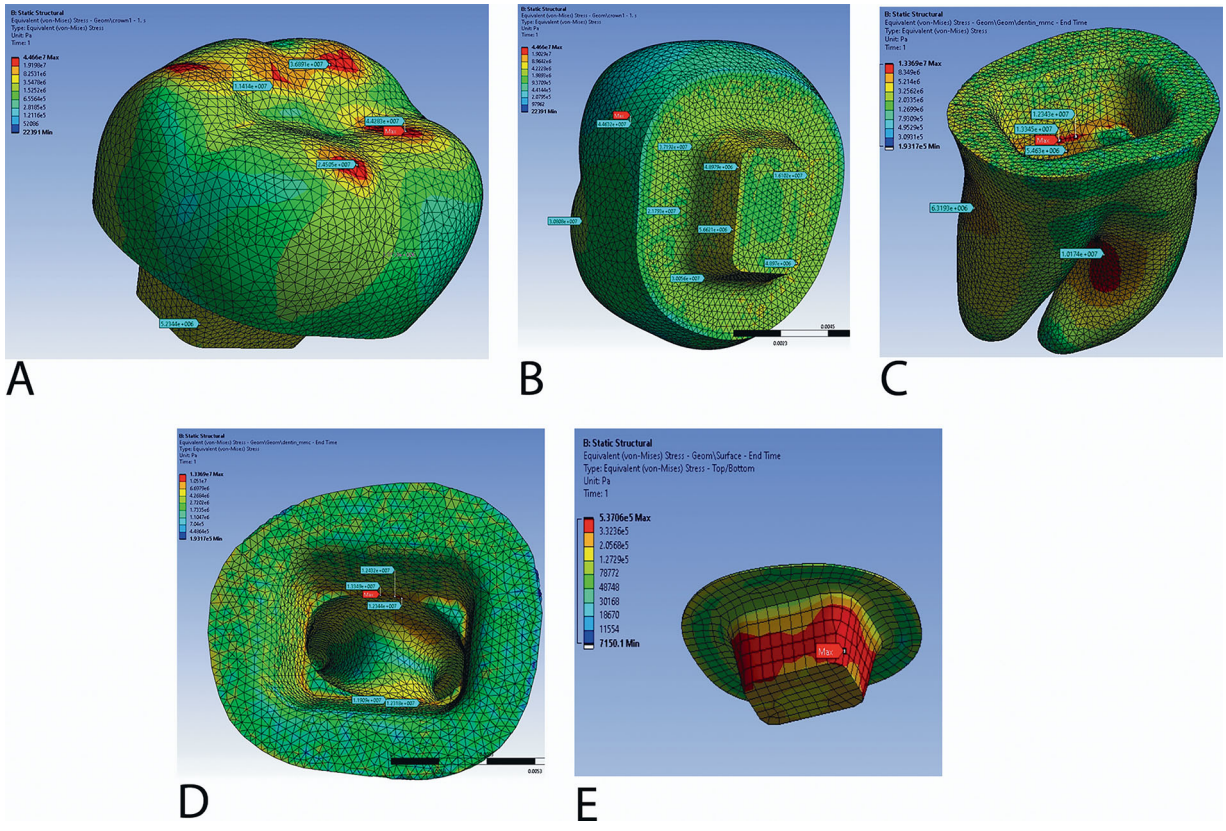


Figure 5. Stress distribution of the endocrown in Model IPS-E a,b: top and bottom surface; c,d: dentin surface, e: adhesive cement surface.

150.77 MPa (Figure 4(a)), whereas the highest mvM stress value in the dentin was 64.238 MPa and concentrated around the cervical region (Figure 4(b), Table 3).

Model IPS-E: In the IPS-E model, the highest mvM stress level was 44.66 MPa (Figure 5(a,b)) and was recorded at the contact loading areas, especially in the mesio-lingual cusp while the highest mvM stress level in the dentin was found in the cervical region of the pulp chamber, which was 13.369 MPa (Figure 5(c,d)). The maximum mvM stress value in the resin cement was concentrated in the pulp chamber cavity wall and reached 0.53706 MPa (Figure 5e, Table 3).

Model C-E: In the C-E model, the highest mvM stress level was 40.625 MPa and was located in the endocrown cusps (Figure 6). In dentin, the highest

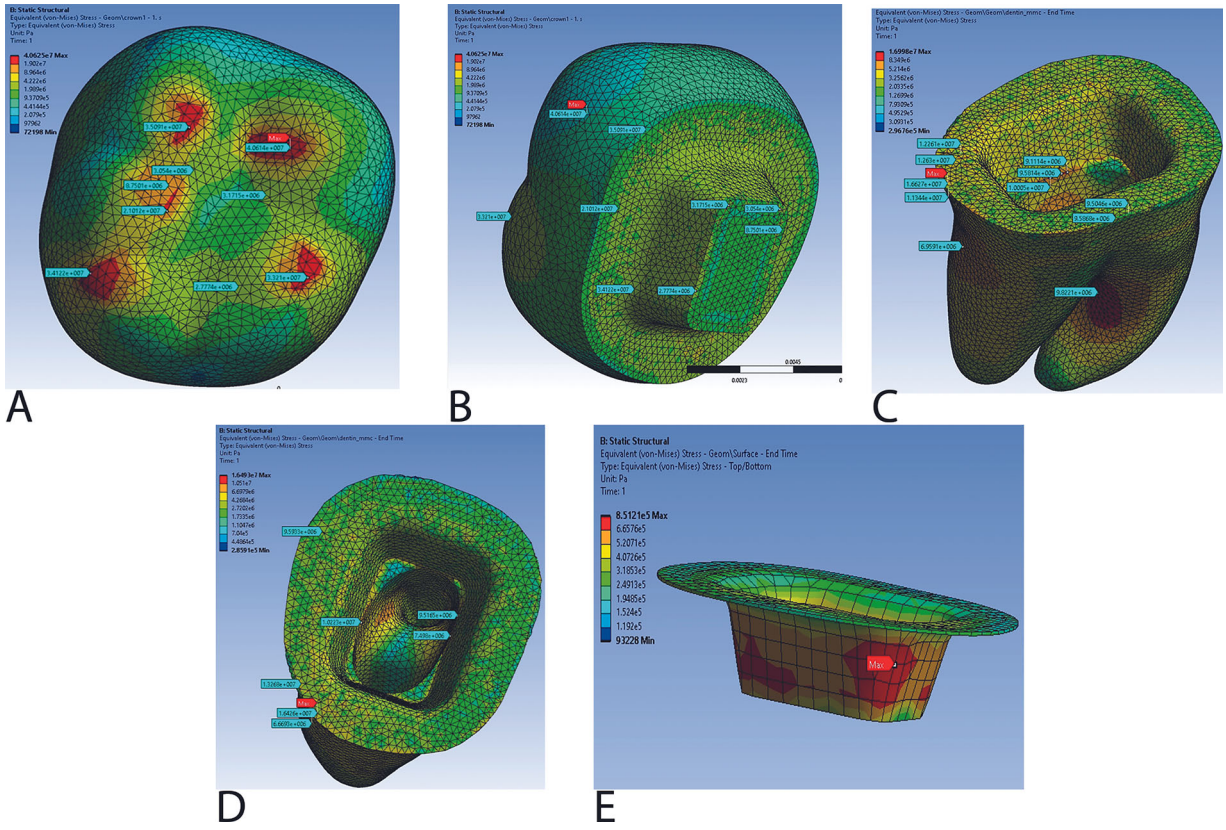


Figure 6. Stress distribution of the endocrown in Model C-E (a,b) top and bottom surface; (c,d) dentin surface; e: adhesive cement surface.

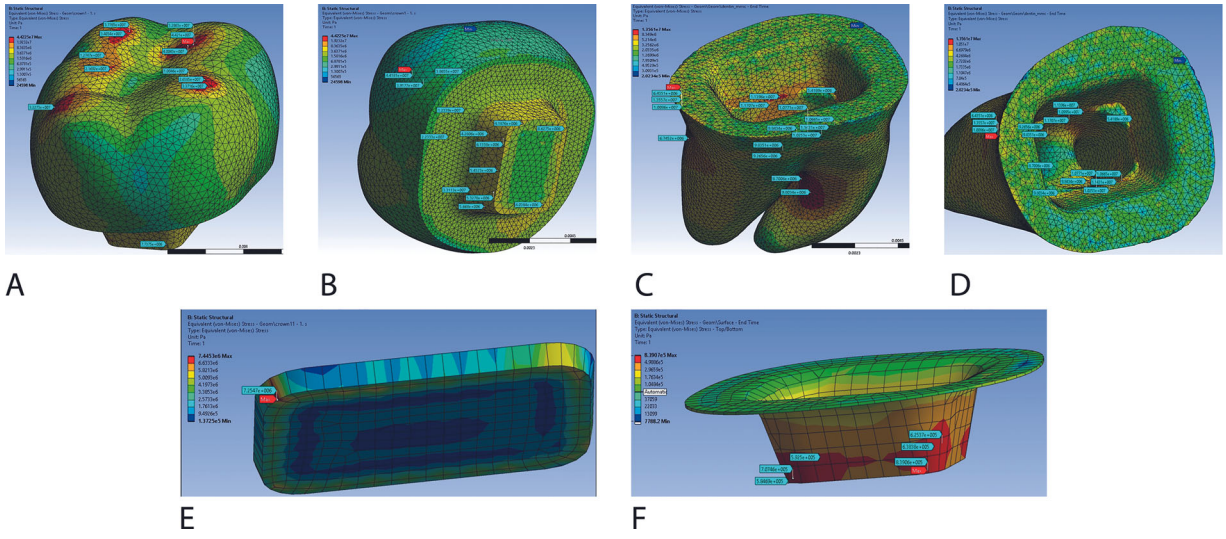


Figure 7. Stress distribution of endocrown restoration in Model IPS-E + fiber (a,b) top and bottom surface; (c,d) dentin surface; e: Fiber f: adhesive cement surface.

mvM stress level was found in the cervical region of the pulp chamber. The level was 16.998 MPa (Fig 6c, d). The maximum mvM stress level of the adhesive cement layer in the C-E model was 0.85121 (Fig 6e).

Model IPS-E + Fiber: In the IPS-E + F model, the highest mvM stres level (44.23 MPa) at the top of the endocrown was situated around the mesio-lingual cusp of the crown surface (Fig 7a and Table 3). The highest mvM stress level in dentin was found at the distal part of the pulp chamber and it was 13.56 MPa (Figure 7(c, d), Table 3). The highest mvM stress level in fiber was 7.45 MPa (Figure 7e). When the stress distrubution of fiber was analysed, higher stress values were found on lateral surfaces versus bottom surfaces.

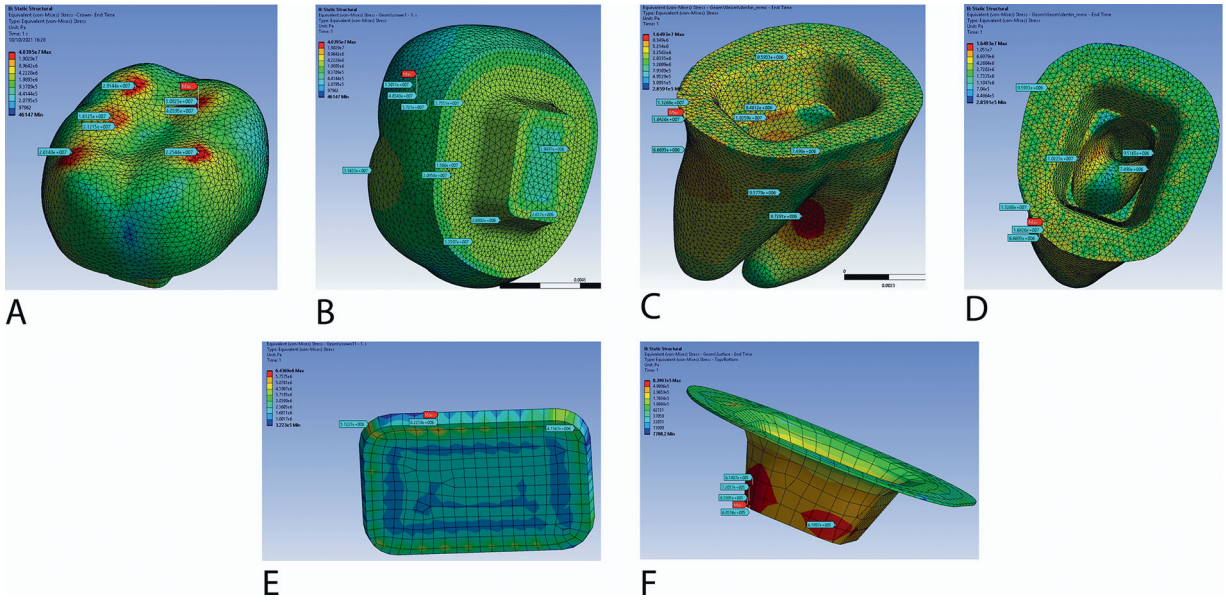


Figure 8. Stress distribution of endocrown restoration in Model C-E + fiber (a,b): top and bottom surface; (c,d) dentin surface; (e) Fiber; f: adhesive cement surface.

The highest mvM value in the resin cement was located in the pulp chamber cavity wall, reaching 0.84 MPa (Figure 7(f)).

Model C-E + Fiber: The highest mvM stress level of the C-E + F model was 40.40 MPa and was located in the endocrown mesio-lingual cusp (Figure 8). The highest mvM stress level in dentin was found in the cervical region of the pulp chamber, which was the same as Model IPS-E (Figure 8(c, d)). The highest stress level in fiber was 6.44 MPa. When the stress values of fiber were compared in the IPS-E and C-E models, lower stress values were determined in Model C-E versus IPS-E (Figure 8(e)). The maximum mvM stress value in the resin cement was located in the cavity wall of the pulp chamber and reached 0.84 MPa (Figure 8(f)).

Discussion

In the present study, the effects of polyethylene fiber insertion and restorative material type on stress distribution in endodontically treated mandibular first molars which were restored by endocrowns was evaluated. Based on the results of this study, changing the stress distribution in restorative material type endocrown restorations did not affect fiber application of the stress distribution. The hypotheses of this study were partially rejected.

Finite element analysis (FEA) is a method that includes a set of computational procedures to calculate the stress and strain occurring in each member. With such a structural analysis, it is possible to determine the stress and strain caused by external force, pressure, thermal change and other factors. Nonlinear finite element analyses: advances and challenges in dental applications (Wakabayashi et al. 2008). The dental periodontal ligament (PDL) is the most deformable tissue in the periodontium and stress-strain in PDL is very important in terms of tooth movement (Fill et al. 2011). In a previous study, Rees (2001) reported that there were differences in stress values between the models in which the periodontal ligament and cortical bone were examined and not examined. Consequently the author suggested that modeling all supporting structures is important when examining stresses distribution in teeth. Also reported that the periodontal ligament and cortical bone should be evaluated to mimic the oral environment in FEA studies. Based on these opinions, in this study, the stress distribution was evaluated by considering the periodontal ligament and cortical bone. Young's modulus and Poisson's ratio of these were assigned based on the data from earlier study (Holmes et al. 1996; Lin et al. 2011).

Previous studies reported that materials with a higher elastic modulus are more rigid and therefore proportionally concentrated more stress (Rocca et al. 2013; Tribst et al. 2018, 2021). In the present study, results showed that an intact tooth had higher mvM stress values than all other groups. On the other hand, among all tested groups the highest stress values were observed on the occlusal loading area in IPS-E (44.66 MPa). It can be assumed that endocrowns with rigid materials protect tooth structures from stress.

Table 3. The mvM stresses in FEA models which occured in Enamal/Crown, Dentin, Fiber and Cement (MPa).

	Enamel/Crown			Dentin			Ribbond			Cement		
	Max (MPa)	Min (MPa)	Mean (MPa)	Max (MPa)	Min (MPa)	Mean (MPa)	Max (MPa)	Min (MPa)	Mean (MPa)	Max (MPa)	Min (MPa)	Mean (MPa)
Intact teeth	150.77	0.72909	22.017	64.238	0.039716	2.2382	–	–	–	–	–	–
IPS-E	44.66	0.022391	2.8861	13.369	0.1.9317	3.1842	–	–	–	0.53706	0.07150	0.17385
C-E	40.625	0.072198	2.7312	16.998	0.29676	3.2992	–	–	–	0.85121	0.093228	0.35917
IPS-E + fiber	44.225	0.024598	2.8397	13.561	0.20234	3.1866	7.4453	0.13725	1.8558	0.83907	0.07788	0.1944
C-E + fiber	40.395	0.046147	2.7277	16.493	0.28591	3.2898	6.4369	0.3223	1.9696	0.84317	0.084192	0.3462

These findings from the current study are consistent with the results of previous studies (Rocca et al. 2013; Tribst et al. 2021).

Mechanical properties of composites such as low modulus of elasticity allow them to exhibit a more flexible structure under loads and to distribute stress more evenly (Magne et al. 2010), but these properties cause increasing stress transfer to the surrounding structure (Gurbuz et al. 2008). According to the results of the previous studies, it has been reported that the greater the modulus of elasticity, the greater the decrease in the distribution of dentinal stress (Yang et al. 2001; Toksavul et al. 2006). Similarly, in this study the stress values in dentin structures were higher in C-E than IPS-E.

In the literature, reasons for endocrown failure were reported as tooth fractures and cohesive failures causing endocrown debonding (Zhu et al. 2020). The cement layer is frequently investigated in studies as cohesive failures often occur in this layer over time (Andre et al. 2013). Tribst et al. (2021) reported that regardless of thickness and type of restoration, more rigid materials tend to prevent the cement layer from receiving excessive stress. This can be explained by the more rigid the crown, the less tensile stress reaches the cement, as this crown absorbs the stress. Materials with low elastic modulus that transmit stress to cement is very important to understand, as cement will have more stress in these situations (Dal Piva et al. 2018). This explains why in this study, the IPS-E group with a more rigid material, stress values in the cement layer were less than the composite endocrowns.

It has been reported that fibers increase the fracture resistance of restorations by transferring the tension from the weak polymer matrix to the fibers with high tensile strength that distribute the tensile lines (Galyan et al. 2019) and its leno weave design can effectively transfer forces throughout the weave without transferring force back into the resin and prevent restoration failure under masticatory forces (Ganesh and Tandon 2006). Based on this point of view, in this study polyethylen fibers were applied under the endocrowns. Regarding stress on the crown and dentin, there was no significant difference between fiber-applied (IPS-E + fiber, C-E + fiber) and non-fiber applied (IPS-E, C-E) endocrowns. However, it was observed that there was an increase in the stress concentration in the applied fiber under the IPS-E Group. These findings are consistent with previous studies which have shown that polyethylene fiber had a stress altering effect (Rudo and Karbhari 1999; Belli

et al. 2006; Sengun et al. 2008) and the researchers demonstrated that the differences in elastic modulus of restorative materials and dentin could affect the stress concentration (Yaman et al. 2003). Consistent with these studies, Gurbuz et al. (2008) stated that fiber + composite materials caused higher stress values in the post core and bonding layer and reported that the mechanical properties of the restorative materials such as the modulus of elasticity has a crucial role on the stress value.

Some limitations should be considered when interpreting the data in this investigation. This is a theoretical study of the mechanical behavior of complex structures found in the oral environment, which can not be completely simulated by FEA. In this study stress distribution in endocrowns was evaluated just under axial load, but oblique loads should be evaluated since they are observed during chewing. In addition, one-type and single piece polythene fibers were used. Using thicker and different fiber materials (such as glass fiber), different endocrown materials or luting agents may change the results. Therefore, more in vitro studies and simulation experiments should support clinical trials.

Conclusion

Within the limitations of this study, several conclusions can be drawn:

1. The mvM stress levels in both lithium disilicat ceramic and resin composite endocrowns were lower than an intact tooth.
2. Although the mvM stress values of crown and dentin were higher in lithium disilicate ceramic endocrown than the composite endocrown, stress values were lower in the cement layer.
3. Fiber application did not change the stress level significantly in both endocrown groups, but fiber absorbed more stress under lithium disilicate endocrowns versus composite endocrowns.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

The author(s) reported there is no funding associated with the work featured in this article.

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