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Conservative restoration of severely damaged endodontically treated premolar teeth: a FEM study

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Abstract The aim of this finite element method (FEM) study was to test two different restorative techniques used for construction of severely damaged endodontically treated premolar teeth using Finite Element Stress Analysis Method. In this study, four types of three-dimensional (3-D) FEM mathematical models simulating (1) a sound lower single rooted premolar tooth with supporting structures; (2) a root-filled lower premolar tooth without lingual cusp, restored with resin composite; (3) a root-filled lower premolar tooth without lingual cusp restored with resin composite in combination with a polyethylene fiber which is placed circumferentially to help to create a composite lingual wall; (4) a root-filled lower premolar tooth without lingual cusp restored with resin composite in combination with a glass fiber post, were modeled. A 300-N static vertical occlusal load was applied on the node at the center of occlusal surface of the tooth to calculate stress distributions. Solidworks/ Cosmosworks structural analysis programs were used for FEM analysis. The analysis of the von Mises stress values revealed that maximum stress concentrations were located at loading areas for all models. Root dentine tissue, lingual cortical bone, and apical bone structures were other stress concentration regions. There were stress concentration differences among the models at root dentine tissue. Although the distribution pattern was similar with composite resin restored tooth model, highest stress values were observed at root dentine in the model restored with post-and-core. Post structure accumulated more stress on its own body. Stress distribution patterns of sound tooth and fiber-reinforced restoration models were found as similar. The present study showed that the use of post material increased the stress values at root dentine structure while reinforcing the restoration with a fiber decreases stress transmission. Fiber-reinforced restoration provided stress distributions similar to sound tooth.

Keywords Endodontically treated teeth · Fiber reinforcement · Biomechanics · Finite element analysis · Stress distribution

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Introduction

Compared to teeth with healthy pulps, root-filled teeth are considered more susceptible to fracture as they possess reduced dentinal elasticity, lower water content, deeper cavities and substantial loss of dentin [1, 2]. The restoration of the pulpless tooth is a critical final step of successful endodontic therapy. Loss of dentin including anatomic structures such as cusps, ridges, and arched roof of the pulp chamber may result in fracture after the final restoration [3].

The prognosis of root-filled teeth depends not only on the success of the endodontic treatment but also on the amount of remaining dentine tissue, and the nature of final restoration [4]. The primary responsibility of the teeth in the

oral cavity is to serve as a mechanical device for the mastication of food [5]. Thus, post core applications are often utilized in the restoration of endodontically treated teeth [6–8].

Also, the development of fiber-reinforced composite (FRC) technology has provided a significant opportunity to tailor materials response and to improve the behavior of existing materials [3]. These new materials and techniques enable the practitioner to approach old problems from a different perspective and thereby achieve unique and innovative solutions [3]. Tooth-colored fiber posts have been introduced and have several advantages over conventional metal posts [9]. Later, fiber reinforcement systems have been introduced in the attempt to increase resin bonded composite durability and damage tolerance [10]. The reinforcement of composite restorations with fibrous assemblies can change the effective fracture strength of the teeth and may be effective in restoring the fractured cusps in endodontically treated teeth through the creation of a strong bridge between the tooth structure and restorative material [3, 10, 11].

Finite element method (FEM) has been shown to be a useful tool when investigating complex systems [12–14]. Knowledge of stress distribution is important to the understanding of fatigue development [15]. Overall stress distribution within the tooth/restoration complex is determined by not only geometry and material arrangement, but also material properties, fixation, and loading conditions determine stress distributions [16]. FE analysis is utilized at current study to evaluate the effects of different restoration alternatives on stress distribution characteristics at endodontically treated teeth without lingual cusp. The null hypothesis tested was that different restoration techniques do not affect the stress distribution within tooth–restoration complex.

Materials and methods

This study was conducted using a 3-D FE method and the Solidworks 2007 9.0.3 structural analysis program (Solidworks Corporation, USA). A three-dimensional FE model was fabricated to represent an endodontically treated single rooted mandibular premolar tooth (Fig. 1a). The model contained a simulated periodontal ligament (PDL) and alveolar bone structure. The geometry used for the tooth model was previously described by Wheeler [17]. On the basis of the root-form geometry of teeth, a simplified 0.25-mm PDL, 0.25-mm lamina dura, and cortical shell (1.5 mm) were developed [18]. The remaining bone was modeled as trabecular bone.

Four different models were investigated to evaluate how the three different restorative options changed the stress distribution: a sound lower single rooted premolar tooth with supporting structures (1—sound tooth); a root-filled
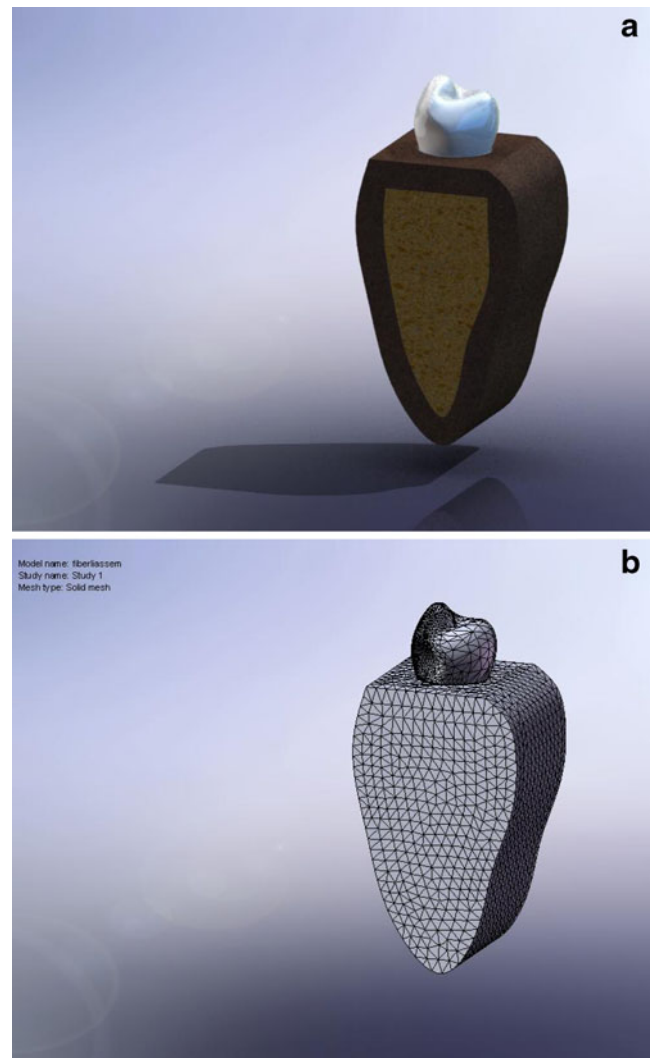
Fig. 1 a Three-dimensional finite element model and illustration of materials involved. b 3-D mesh

lower premolar tooth without lingual cusp, restored with resin composite without fiber reinforcement (2—composite resin); a root-filled lower premolar tooth without lingual cusp restored with resin composite in combination with a polyethylene fiber (Ribbond, Ribbond, Seattle, WA) which is placed circumferentially to help to create a composite lingual wall following a protocol previously described by Deliperi et al. [10] (3—fiber reinforcement). In this method, the dentin surfaces are treated with an adhesive resin, light-cured, and a matrix band is placed circumferentially. An approximately 1±0.5-mm-thick lingual wall is created using composite resin and light-cured for 40 s. The inner axial cavity surfaces are then lined with a flowable resin and kept uncured. A piece of polyethylene fiber (according to the dimensions of the tooth) is cut and wetted using an unfilled adhesive resin. After removing the excess adhesive towards the fibers direction using a hand instrument, the fiber is placed circumferentially inside the cavity walls and

embedded tightly into the flowable resin. After curing for 20 s, the rest of the cavity is filled using the same composite resin and cured for 40 s.

The last model of the study was a root-filled lower premolar tooth without lingual cusp restored with resin composite in combination with a prefabricated glass fiber post (ParaPost Fiber White, Coltene/Whaledent, Hauptsitz, Switzerland; 4—post retained; Fig. 2a–d).

Initially, cross-sections of structures included in mathematical model were sketched at front and right planes separately for each unit at computer environment. Coordinates of the contouring points were then entered as border nodes of mathematical models. These nodes were joined to form each structures 3-D volume that together defined the final geometry of FE model. The geometric models were meshed with tetrahedral quadratic elements (Fig. 1b). Each mathematical model included approximately 62,300 nodes and 47,000 solid elements. The bottom exterior nodes of the alveolar bone in the FEM models were fixed in all directions as the boundary condition. A 300-N static vertical occlusal load was applied on the node at the center of occlusal surface of the tooth to calculate stress distributions.

Materials used in study were assumed to be homogenous, and isotropic. Elastic properties of materials (Young's modulus (E) and Poisson's ratio (μ)) were determined from the literature and given in Table 1 [5, 12, 19–22].

Results

Results were presented by considering Von Mises criteria [23–27]. Calculated numerical data were transformed into color graphics to better visualize mechanical stresses in the models. Bucco-lingual cross-sections of 3-D whole model view were presented for each restoration type. All stress values were indicated in megapascals (MPa).

The analysis of the von Mises stress values revealed that maximum stress concentrations were located at loading areas for all models. However, the maximum von Mises stress value was observed at post retained model with 24.50 MPa (Fig. 3). It was followed by composite resin restoration model by 21.20 MPa (Fig. 4), 19.73 MPa by sound tooth (Fig. 5), and 18.98 MPa by fiber reinforcement (Fig. 6). Also, root dentine tissue, lingual cortical bone, and apical bone structures were other stress concentration regions. There were stress concentration differences among the models at root dentine tissue (4.77, 4.95, 4.29, 5.70 MPa at sound tooth, composite resin, fiber-reinforced composite resin and prefabricated post retained models, respectively). Highest root dentine stress value was observed at post-and-core restored model with 5.70 MPa. The maximum von Mises stress values of structures at different models were summarized at Table 2. Distribution pattern was similar at sound tooth model, the model with composite resin restoration and the model with fiber-reinforced composite resin restoration. Stress was starting at force application area, and directing to lingual–apical aspect through lingual root dentine. Stress distribution pattern at prefabricated post retained model was different from that the other models. It was starting at same area, but directing more apically through post materials body. Post structure accumulated more stress on its own body (9.56 MPa). Stress distribution patterns of sound tooth and fiber-reinforced restoration models were found as similar.

Fig. 2 Illustration of different restorative techniques, **a** sound tooth, **b** composite resin, **c** fiber reinforcement, and **d** post retained models
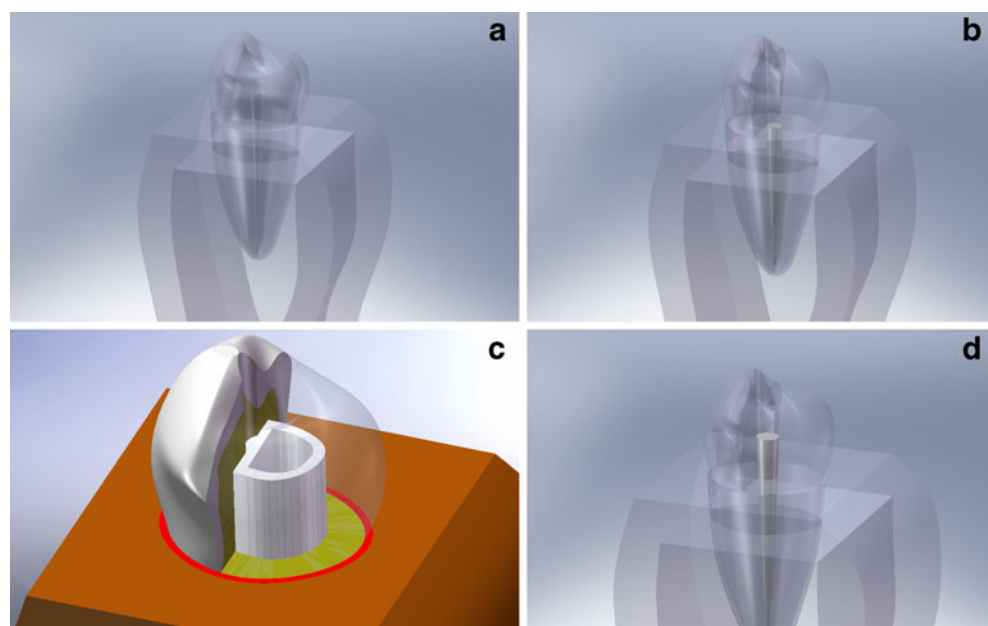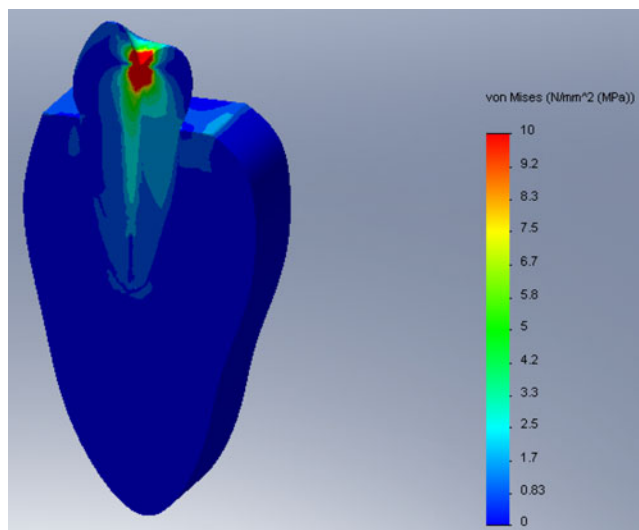
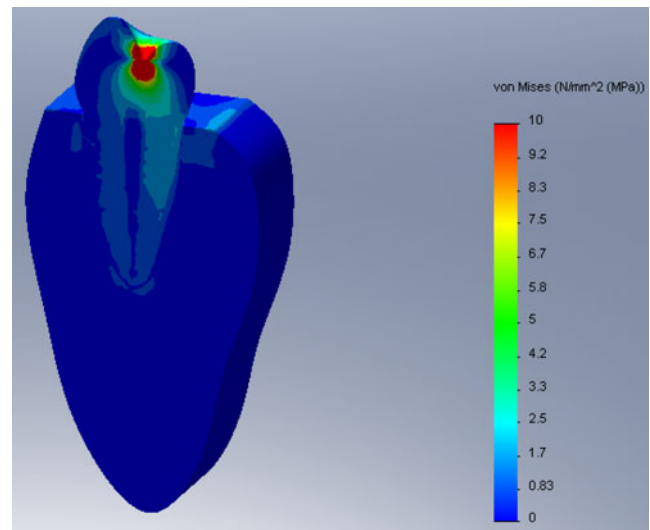**Table 1** Mechanical properties of investigated materials

Material	Elastic modulus (E; GPa)	Poisson's ratio (μ)
Enamel [19]	41	0.31
Dentin [20]	18.6	0.31
Periodontal Lig. [22]	0.0000689	0.45
Gutta-Percha [5]	0.14	0.45
Cortical bone [21]	13.7	0.30
Cancellous bone [21]	1.37	0.30
Composite [12]	12	0.30
Glass fiber post [12]	40	0.26
Fiber reinforcement [20]	23.6	0.32

Discussion

This FEM utilized study showed that the von Mises stress distribution characteristics at restoration-tooth complex of sound tooth, direct composite resin restored, and fiber-reinforced composite resin restored tooth models were similar. Thus the null hypothesis is accepted in part. On the other hand, the distribution of stress in prefabricated glass fiber post restored tooth model was different. Therefore, we have to reject the hypothesis for post restored tooth model. These results were similar to a study of Eskitascioglu et al. [20] that compared two different restorative techniques and stated that stresses have been accumulated along the post core system by use of a post of high elastic modulus. Current study adds the comparison of sound tooth and fiber-reinforced restoration of an endodontically treated tooth without usage of post to this findings. Modifications that would reduce or eliminate the interfacial stress concentration within the composite
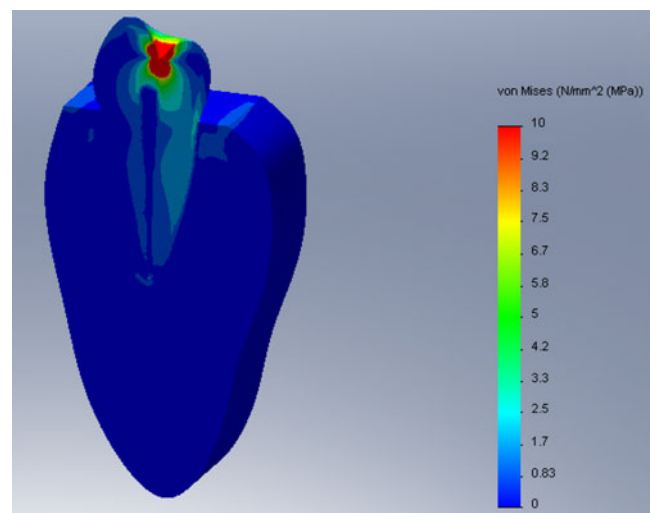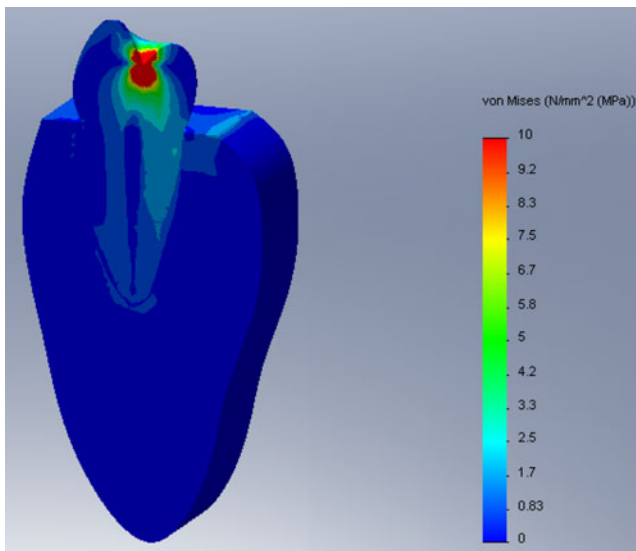

Fig. 4 Distribution of von Mises stresses (MPa) in bucco-lingual section of composite resin restored tooth model. *Blue to red colors* represent stress values from lower to higher, respectively

restoration may increase the bond strength by increasing the force required to create and propagate a crack through the interfacial composite/adhesive bonding resin complex [28]. Fiber reinforcement materials are often used for this purpose and they provided conservative and aesthetic restoration of endodontically treated teeth with extensive tooth structure loss [11, 28, 29]. The higher modulus of elasticity and lower flexural modulus of the polyethylene fiber are believed to have a modifying effect on the interfacial stresses developed along the etched enamel/resin boundary [30]. Embedding a Leno Wave Ultra High Modulus polyethylene fiber into the bed of flowable resin under an extensive composite restoration increases both the fracture strength in root-filled

Fig. 3 Distribution of von Mises stresses (MPa) in bucco-lingual section of post retained tooth model. *Blue to red colors* represent stress values from lower to higher, respectively

Fig. 5 Distribution of von Mises stresses (MPa) in bucco-lingual section of sound tooth model. *Blue to red colors* represent stress values from lower to higher, respectively

Fig. 6 Distribution of von Mises stresses (MPa) in bucco-lingual section of fiber-reinforced restoration model. *Blue to red colors* represent stress values from lower to higher, respectively

molars with MOD cavities [28] and the microtensile bond strength to dentin [29] but decreases microleakage in cavities with a high c-factor [31].

Ko et al. [32] indicated that posts changed dentin stress substantially under compression in vertical loading. Confirming their results, the posts affected the dentin stress distribution in this study. It was reported that the stress concentrations at the cervical region are mostly because of the increased flexure of the compromised tooth structure, while stress concentrations at the apical region are generally due to the taper of the root canal and characteristics of the post [4]. The regions of high stress concentration are also associated with the apical termination of the post [4]. Confirming these findings, stress concentration areas were located at post system or cervical dentin region via different restorative material (with different elastic modulus) within root canal at current study.

The size of occlusal force is selected as 300 N. However, it is not necessary for this force to match the reality exactly because standardization between conditions has been ensured in the current study and the conditions have been compared qualitatively with each other. Chen and Xu [13] have emphasized that the value of FEM modeling is in relative values calculated at distribution pattern.

The FEM results are presented as stresses distributed in the investigated structures. The stress conditions contain combinations of tensile, compressive, and shear stress components, which are often expressed in von Mises equivalent stresses [24, 33]. This study also chose von Mises stresses for presentation of the results. However, it should be emphasized that the von Mises stress does not distinguish between compressive or tensile stresses. Since compressive strength of dentin is considerably higher than its tensile strength, stress concentrations with predominant tensile stress components will have a higher risk of failure. As with many in vitro studies, it is difficult to extrapolate the results of this study directly to a clinical situation. The model used in this study implied several assumptions regarding the simulated structures. Materials used in this study were assumed to be homogeneous and isotropic, including the fiber-reinforced materials. The properties of the materials modeled in this study, particularly the living tissues, however, are different. This is one of the limitations of FEM studies. Clinical experiences indicate that most fractures in restorations occur after several years. Generally, such failures are unrelated to episodes of acute overload, but result from fatigue failure. Consideration of only one-point load location and the absence of dynamic loading is another limitation of the study. Also, it is important to point out that the stress distribution patterns may have been different depending on the materials and properties assigned to each layer of the model and the model used in the experiments. Thus, the inherent limitations in this study should be considered. On the other hand, FEM studies give the clinician a prediction of the success of a restoration in oral conditions in a biomechanical perspective. And, as stated before, FEM has been shown to be a useful tool when investigating complex systems [12–14]. Further studies that better simulate the oral environment which include fracture strength are recommended.

Conclusion

Within the static one-point loading condition of this study, the following conclusions were drawn:

1. The use of a post material increases the von Mises stress values at root dentine structure while reinforcing the composite restoration with a fiber without a post

Table 2 The maximum von Mises stress values of structures involved in different models (MPa)

	Enamel	Composite	Fiber	Post	Dentin	Pulp T.	Gutta P.	P. lig.	Cortical B.	Spongy B.
Sound tooth	19.73	–	–	–	4.77	0.45	–	0.42	1.63	0.14
Composite R.	5.66	21.20	–	–	4.95	–	0.21	0.29	2.13	0.17
Fiber reinf.	6.34	18.98	8.49	–	4.29	–	0.24	0.33	2.39	0.14
Post retained	10.60	24.50	–	9.56	5.70	–	0.26	0.42	2.21	0.14

providing lower von Mises stress values at tooth structures

2. Restoration of a severely damaged endodontically treated tooth by a fiber reinforcement restoration technique may be recommended instead of restoration with a post system in order to acquire more similar stress distribution to the sound tooth.

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