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Research Article

Influence of Ferrule Height on Stress Distribution and Deformations of Central Incisor Under Different Loads (Finite Element Study)

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Abstract

Aim: Estimating ferrule length effect on central incisor stresses and deformations under different load cases.

Materials and Methods: Three finite element models were developed to simulate endodontically treated central incisor with three ferrule lengths (1, 2, 3 mm) in combination with (IPS E-max Press) crown and glass fiber post. Laser scanning and CAD modeling were used to create geometry. ANSYS was used for meshing and analysis of models under three occlusal patterns (edge-to-edge occlusion, normal occlusion, and deep bite).

Results: Models results were within physiological limits, no failure were expected. Minor differences were in deformations and stresses distributions with changing ferrule length under the same loading conditions.

Conclusion: Increasing ferrule length improved the performance under load and reduced deformations and stresses on all parts.

Keywords: *Central Incisor; Finite Element; Ferrule Length; Stress Distribution; Deformations*

Introduction

Ferrule usually described as the heart of tooth preparation when endodontic treatment uses post and core. Its length is equivalent to vertical band between remaining tooth structure and crown preparation. It reduces the stress on root, helps in withstanding occlusal forces, preserving proper seal of the cement and decreasing the stresses at the interface between the post and core [1].

It is the band of metal in case of metal ceramic crowns or ceramic in case of all ceramic crown as in this study that encircles the remaining tooth surfaces [2]. Post without the ferrule will act as a wedge with more possibility of root fracture [3]. Improved composites are used recently with fiber posts as cores.

The main factors influencing the strength of the endodontically treated tooth are the remaining tooth structure thickness [4] and the ferrule.

The adhesive bonding techniques are now widely used to restore endodontically treated teeth, but there is a need to have similar elastic properties as dentin to help in stress distribution and decrease the possibility of fracture.

In addition, the magnitude and direction of load can influence the resistance of central incisors to fracture. The stresses on the restoration that is done after endodontic treatment is not uniform and in different axes. Stresses are not distributed in a homogenous way due to the geometry of the post and core system [5].

In a research cone before it was found that the stress pattern was similar regardless of the post material [6].

The rationale of this finite element study is to study ferrule length effect (three models were created) on palatal surface of crowned endodontically treated central incisor stresses and deformations under different load conditions. The null hypotheses is that increasing the ferrule length (1, 2 and 3 mm) will improve the performance under different loading conditions (edge to edge occlusion, normal bite and deep bite occlusion) and will reduce the deformations and stresses on all parts of the studied system.

Methods

Three finite element models for maxillary central incisor were developed. The central incisor geometry was acquired by using laser scanner (Geomagic Capture, 3D Systems, Cary, NC, USA). It produced data file containing a cloud of points coordinates, see figure 1. A software was required (Rhino 3.0 - McNeel inc., Seattle, WA, USA) to trim the newly created surfaces by the acquired points. Then, the solid (closed) tooth geometry was exported to finite element program as STEP file format [17].

(a) *(b)*

Figure 1: *(a) Laser scanner, (b) Scanned tooth.*

Cortical and spongy bone models were created by commercial computer-aided design software AutoDesk Inventor software version 8.0 (Autodesk Inc., San Rafael, CA, USA). Bone geometry was simplified and simulated as two coaxial cylinders, inner one represents the spongy bone with 14 mm diameter and 22 mm height, that filling the internal cylindrical space of the other cylinder (shell of 1 mm thickness) that represents cortical bone (outer diameter of 16 mm and its height of 24 mm) [18,19]. Set of Boolean operations on ANSYS environment (ANSYS Inc., Canonsburg, PA, USA) were made to finalize the model as presented in figure 2 and 3. All materials were considered isotropic except the glass fiber post, liner and elastic, which fed to ANSYS as listed in table 1. The meshing of the models' components was done by 3D brick solid element "187" which has three degrees of freedom (translation in main axes directions) [20]. The resulted numbers of nodes and elements (Listed in table 2) were optimized for accurate results and suitable analysis time.

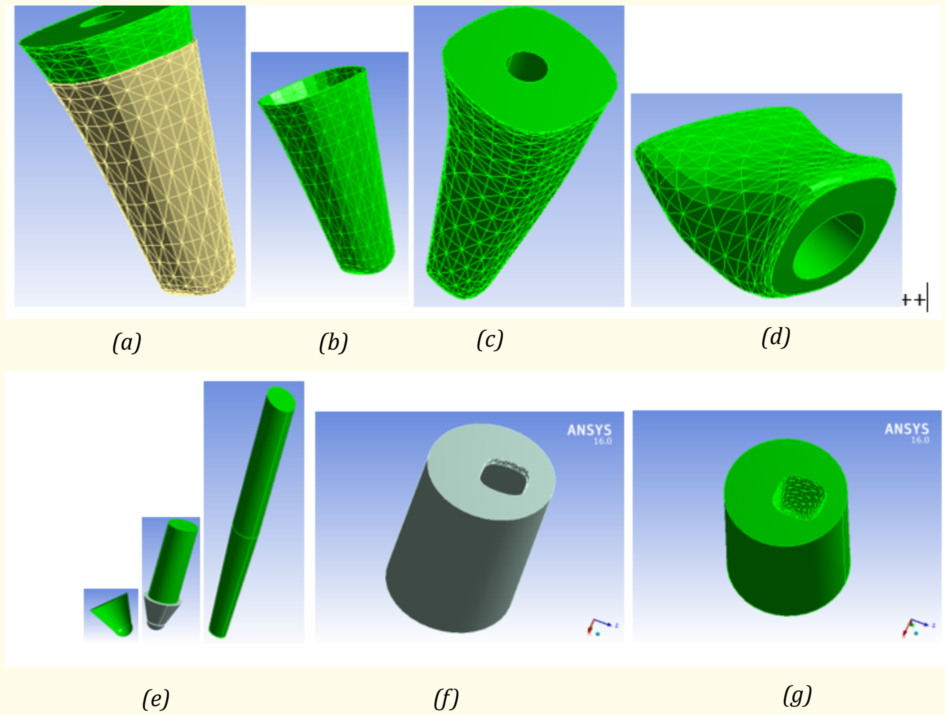

Figure 2: *Models components (a) PDL + Root, (b) PDL, (c) Root, (d) crown, (e) MTA + GP + Post, (f) Cortical, (g) Spongy.*

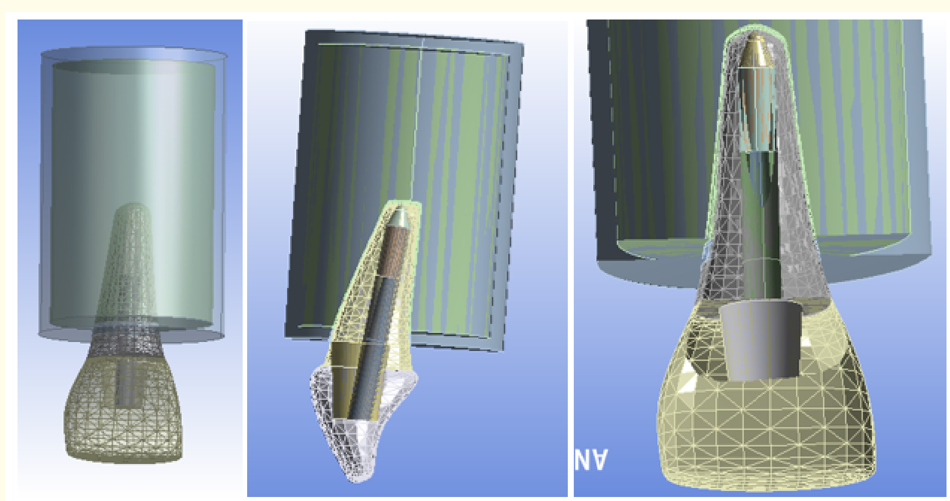

Figure 3: *Final model(s) and cut views from ANSYS screen.*

Material	Young's Modulus [MPa]	Poisson's ratio
Cortical bone	13,700	0.3
Cancellous bone	1,370	0.3
Periodontal Ligament (PDL)	0.0689	0.45
Root (Enamel)	84,100	0.31
MTA	15,700	0.23
Gutta percha (GP)	140,000	0.45
Luting Cement	8,130	0.3
Post: Exacto glass fiber Angelus, Brazil	E_x = 9,500 E_y = 37,000 E_z = 9,500 G_{xy} = 3,544.8 G_{yz} = 3,544.8 G_{xz} = 1,456.7	υ_{xy} = 0.34 υ_{yz} = 0.34 υ_{xz} = 0.27
Core	15,800	0.24
Crown: IPS e-max press	97,500	0.24

***Table 1:** Material properties.*

	Model #1		Model #2		Model #3	
Volume	Number of Nodes	Number of Elements	Number of Nodes	Number of Elements	Number of Nodes	Number of Elements
Crown	95,687	65,935	90,885	63,001	24,580	16,131
Core	3,171	531	3,046	532	3,475	648
Post	19,147	3,856	19,553	3,802	19,406	4,424
Cement	8,713	3,964	8,713	3,964	25,167	13,155
GP	4,235	875	4,235	875	4,966	1,062
MTA	12,240	8,615	12,240	8,615	38,180	26,575
Root	65,823	45,502	85,022	58,523	110,693	75,959
PDL	10,743	5,238	11,031	5,530	10,846	5,426
Cortical bone	64,160	37,958	64,160	37,958	83,201	49,950
Spongy bone	116,036	80,692	116,036	80,692	114,299	78,993

***Table 2:** Mesh density.*

The lowest plane of the model was considered fixed in the three directions as a boundary condition. While the applied loads were set as; 50N, directed with 135º oblique angle from the vertical plane, to the following points:

1. Lingual slope of incisal edge.
2. The junction between incisal and middle thirds.

3. The beginning of cingulum.

Nine linear static analyses were performed on a personal computer (Intel Core i7 processor, 2.4 GHz, 6.0 GB RAM), using commercial multipurpose finite element software package (ANSYS version 16.0).

Results

Each analysis resulted in many kinds of deformations and stresses distributions ranged from minimum value(s) to extreme one(s). The impression was taken from the results that all extreme deformations and stresses were located within acceptable physiological limits. Minor or negligible changes were noticed by changing ferrule length under the same loading condition.

Figure 4-6 demonstrate sample for one part of each model showing total deformation on model #3 crown, Von Mises stress distribution on model #2 root and Von Mises stress distribution on model #1 cortical bone respectively. Comparison between the three models extreme total distribution and Von Mises under the three loading cases are also presented.

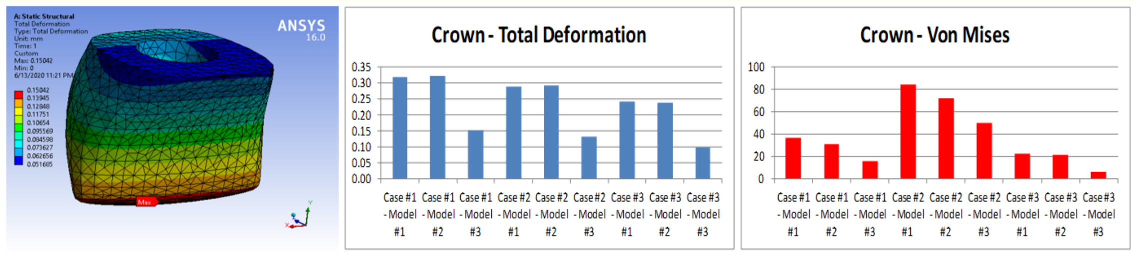

Figure 4: *Model 3, crown total deformation distribution and results comparisons.*

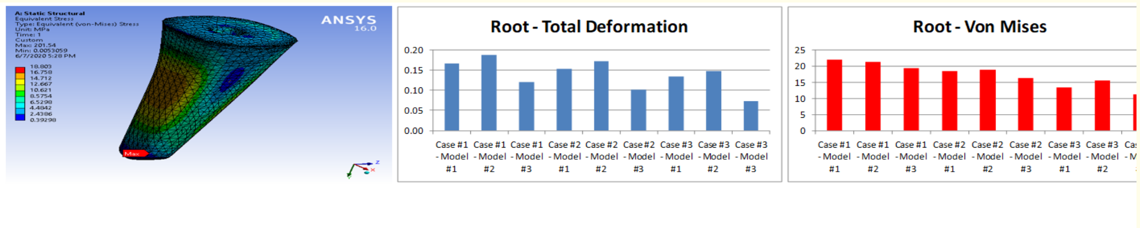

Figure 5: *Model 2, root Von Mises stress distribution and results comparisons.*

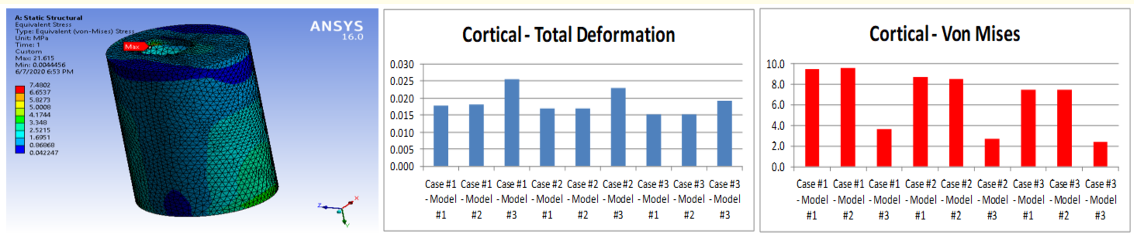

Figure 6: *Model 1, cortical Von Mises stress distribution and results comparisons.*

Total deformation extreme values showed fixed trend on crown, core, post, cement, root, PDL, and spongy bone. Whatever the occlusion type (edge to edge bite, normal bite, and deep bite) ferrule lengths of 1 and 2 mm total deformations were equivalent while the longer ferrule length (3 mm) showed less total deformation by 10 to 30%. On the other hand, model parts like GP, MTA, and cortical bone with longer ferrule length (3 mm) showed higher values of extreme total deformation by 10 to 20% more than shorter ferrule lengths that showing nearly the same value.

Von Mises extreme values showed same trend on crown, core, and root where the stress value decreased gradually with increasing ferrule length.

Whatever the occlusion type (edge to edge bite, normal bite, and deep bite) Feruule lengths of 1 and 2 mm stresses were equivalent, while the longer ferrule length (3mm) showed less Von Mises stress on post, cement, GP, MTA, PDL, cortical and spongy bone by about 50 to 70%.

Discussion

The FEA is an engineering method that is used to analyze the stresses and strains of different materials involved in the prosthetic treatment [7]. It is easy to change variables; there is good standardization and accurate results obtained. Using computer software, the problem can be analyzed and numerical analyses can be done. Analysis of stresses on root dentin is difficult to be done clinically.

The maxillary central incisor behave mechanically as an elastic beam fixed at its lower end during function and as cantilever with lateral loads [8]. As the modulus of elasticity of dentin is 18 GPa so restoring the missed tooth structure with resin materials as fiber posts with modulus of elasticity 12.5 GPa will lead to more stress distribution and less possibility of fracture.

In this study, resultant stresses were within physiological limits, that no failure were expected under the applied loads. As in a study by Valdivia., et al. in 2018 where the strain on the tooth was stable in case of ferrule preparation [9]. Magne., et al. in 2017 confirmed that the presence of ferrule is the most important factor in increasing the tooth resistance [10]. In a study by Kayabasi in 2018 low stresses were obtained by using the fiber glass post cemented by adhesive resin cement with low modulus of elasticity [11]. These posts have high tensile strength and Young's modulus near that of dentin. Also, bonding transmits stresses between post and dentin and decrease possibility of fracture.

Increasing ferrule length improves performance, reduces deformations and stresses on all parts with different percentages. Von Mises stress on post, cement, GP, MTA, PDL, cortical and spongy bone may be reduced by 50 to 70% with increasing ferrule length from 1 to 3 mm. As found by Xie., et al. in 2020, where bovine incisors were used, subjected to fatigue loading and resistance to fracture increased with increasing the ferrule thickness [12]. Increasing the ferrule thickness has the same importance for fracture resistance as increasing length. Ding., et al. in 2020 in their in vitro and finite element study found that root fracture resistance was more with crown dentin ferrule obtained with orthodontic eruption. However, a 4-year survival analysis by Joluski., et al. in 2014 showed that the remaining tooth structure and bonding materials have no effect on failure. Another invitro study by Kul., et al. in 2020 confirmed our study results by showing that regardless the post material and modulus of elasticity, prevention of the failure in endodontically treated teeth depends on the ferrule [14].

Measuring deformation helps in understanding of fracture process [16]. In our study total deformation with longer ferrule length (3 mm) was less by up to 30% in comparison to shorter one (1 mm) on crown, core, post, cement, root, PDL and spongy bone. Results agreed with Ausiello., et al. in 2017 that found in tooth restored with fiber post, ferrule decreased tensile stresses in the crown, luting agent and root [15]. Regarding the root, tensile stresses were 1.8 - 2.1 times less in case of using ferrule than not using. Regarding the luting agent, maximum tensile stresses were 6.2 - 32.1 times less with ferrule. Valdivia in 2018 found that with aging, in case of no ferrule there was more root dentin deformation than with using 2 mm ferrule. The deformation was not influenced by the presence of ferrule [9].

The results showed that ferrule is a very important biomechanical feature for endodontically treated anterior tooth with a crown retained by a post. More clinical studies to show the best ferrule dimensions are needed to confirm our results.

Conclusion

The three ferrule lengths (1, 2 and 3 mm) results were within physiological limits, no failure were expected under loads. Small and minor differences were recorded in deformations and stresses distributions with changing ferrule length under the same loading conditions. Increasing ferrule length improves the performance under load, reduces deformations and stresses on all the studied system.

Ethical Approval

This research does not require ethical approval and followed the Helsinki declaration.

Conflict of Interest

The authors declare that they have no conflict of interest.

Authors Contribution

All authors contributed in all parts of the study.

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