Frontiers in Dentistry

The Effect of Ferrule/Crown Ratio and Post Length on the Applied Stress and Strain Distribution to the Endodontically Treated Maxillary Central Teeth: A Finite Element Analysis

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Article Info

Article type:
Original Article

Article History:
Received: 25 May 2022
Accepted: 02 Dec 2022
Published:10 May 2023

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ABSTRACT

Objectives: One of the most common methods used for the reconstruction of endodontically treated teeth is post and core and crown. Various factors such as the remaining tissue above the cutting margin (ferrule) affect the fracture resistance of teeth restored with post and core and crown. This study aimed to investigate the effect of ferrule/crown ratio (FCR) on the strength of maxillary anterior central teeth using finite element analysis.

Materials and Methods: A 3D scan of a central incisor was obtained, and the data were transferred to Mimics software. Then, a 3D model of the tooth was designed. Next, 300N load was applied at a 135° angle to the tooth model. Force was applied to the model both horizontally and vertically. Ferrule height was considered to be 5%, 10%, 15%, 20%, and 25% in the palatal surface and 50% in the buccal surface. The length of post in the model was 11, 13, and 15mm.

Results: By increasing the FCR, stress and strain distribution increased in the dental model and decreased in the post itself. As the horizontal angle of load application increased, the level of stress and strain created in the dental model increased as well. The closer the force application site to the incisal area, the higher the stress and strain would be.

Conclusion: Maximum stress was inversely correlated with FCR and post length. In ratios of 20% and higher, insignificant changes occurred in stress and strain patterns in the dental model.

Keywords: Finite Element Analysis; Tooth Crown; Root Canal Therapy; Dental Stress Analysis

➢ **Cite this article as:** Mosharaf R, Abolhasani M, Fathi AH, Rajabi A. The Effect of Ferrule/Crown Ratio and Post Length on the Applied Stress and Strain Distribution to the Endodontically Treated Maxillary Central Teeth: A Finite Element Analysis. *Front Dent.* 2023:20:16.

INTRODUCTION

The reconstruction of endodontically treated teeth is a highly important issue in dentistry. Reconstruction of endodontically treated teeth is important due to the esthetic. The importance of dentition and smile esthetic has increased and therefore procedures such as using golden ratio in smile design and using crown and post and core system performed [1,2]. Moreover, root canal treatment not only causes clinical symptoms and discomfort after the treatment [3,4], but also the endodontically treated teeth are weaker and more prone to fracture than the vital teeth. The main reason for this phenomenon is a change in the biomechanical behavior of the supporting structures of the tooth. Many factors affect the durability and longevity of these teeth. A vital factor involved in the endodontically treated teeth is the maintenance of dental structures [5-7]. This treatment weakens the remaining tooth structure due to changing the properties of the supporting structure of the tooth such as bones and periapical tissues [8]. These changes are often proportional to the caries rate and removal of dental tissues. The coronal structures of endodontically treated teeth are weaker and more fragile than those of the vital teeth when force is applied. Their sustainability is also lower than that of the vital teeth, especially when they are used as a bridge base or a removable partial denture [9,10].

A post and core system is a technique used to reconstruct the endodontically treated teeth with much coronal structure lost. In general, the post and core system is used to replace the lost coronal tissue. In these systems, the post in the root canal acts as an anchorage for the remaining coronal tissues of the tooth, which provides an appropriate gear for the dental crown [11,12].

Using software and digital tools are lucrative in various fields of dentistry such as oral radiology and endodontics [13,14]. Nowadays, one of the most advanced methods in the simulation of tooth structure characteristics is the use of finite elements. This method is a widely used method for the simulation of the mechanical effects of masticatory forces on periodontal ligaments and dental hard tissues. In this method, the special coefficient of elasticity and Poisson ratio are considered for each part of the model [15,16].

Ferrule is one of the main elements in tooth preparation that is used for post and core. Studies have shown that the minimum remaining coronal tissue (crown ferrule) to increase the fracture resistance is 2mm [17]. It has been documented that crown ferrule can enhance the resistance to occlusal forces applied to the tooth. It also decreases the forces applied to the tooth, including wedging or bending moments while placing the post, and helps to improve the marginal fit of the crown [18].

Some researchers have reported that the minimum ferrule required to increase the fracture resistance of a tooth is at least 1mm. Moreover, the teeth with 1-mm ferrule have a poorer performance than the teeth with 2mm ferrule [19]. It has been proven that the maximum force is applied to the cervical region of the tooth; hence, the higher is the ferrule height, the lower is the force applied to the tooth. In addition, when all four walls exist at an adequate height, the maximum fracture resistance will occur. In 2010, Mahdavi Izadi et al. investigated the effect of different ferrule designs on the fracture resistance of maxillary anterior teeth restored with post and core. They divided 40 extracted endodontically treated teeth into four groups. The first group included 10 teeth with 2mm ferrule above the CEJ, the second group consisted of 10 teeth with 2mm ferrule on the palatal wall of the tooth, the third group comprised 10 teeth with 2mm ferrule on the buccal wall, and the fourth group included 10 teeth with 2-mm ferrule on both palatal and buccal walls and interdental concavity. The results of their study showed the maximum fracture resistance in group 3 and minimum fracture resistance in group 1 [20].

Dikbas et al. evaluated different ferrules heights in endodontically treated maxillary anterior teeth restored with fiber post and composite cure. They divided 60 teeth into six groups: the first group (control group) included teeth with a full-crown prosthesis, the second group included teeth with 2mm ferrule, the third group consisted of teeth with 2mm ferrule in the vestibular area, the fourth group comprised teeth with 2mm ferrule in the palatal region, the fifth group included teeth with 2mm ferrule in vestibular and palatal regions and interdental concavity, and the sixth group involved teeth without ferrule. The results indicated, except for group 1 with the highest fracture resistance, group 4 had the highest resistance and group six had the lowest resistance [18].

Madfa et al. [15] conducted a study on the tensile strength distribution of maxillary anterior teeth restored with prefabricated cast posts. They included four 3D models of maxillary anterior teeth made with nickel-chrome, gold, titanium, and fiberglass. A force of 100N was applied to all models obliquely. In all models, the highest level of stress was observed in the palatal area of the root, which was reduced from the outer part to the inner part of the root. The tensile stress concentration was lower in the gold and fiberglass posts than in the other two groups. The maximum tensile stress was found at the palatal region of the nickel-chrome post. Its minimum level was observed in the palatal region of fiberglass posts, and maximum amplitude of tensile stress interference was seen in the pulpal region of nickel-chrome posts. Fiber posts acted better than other posts in tensile strength transfer [15]. Finite element analysis was used in this study to evaluate the effect of FCR on the distribution of stress applied to the endodontically treated maxillary teeth using post and core.

MATERIALS AND METHODS

A maxillary central tooth with no caries which was extracted due to periodontal problems was used in the current study. This tooth was kept in hypochlorite before application of the required changes. After making an access cavity in the tooth, the step-back technique was used to prepare the root canal, and 2.5% sodium hypochlorite was used to irrigate the root canal during preparation. Using the data of the 3D scanner, a 3D model of the tooth was produced by Mimics software (Fig. 1).

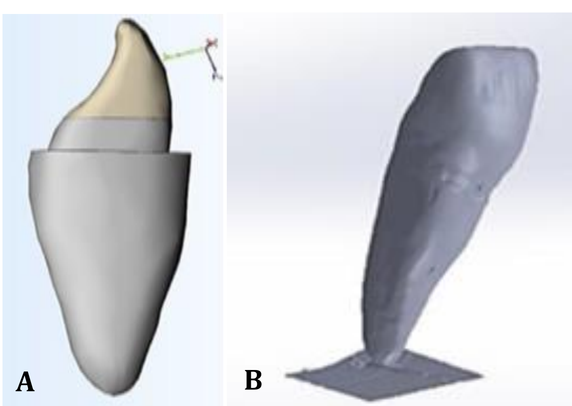

Fig. 1. A maxillary central tooth modelled by Mimic software (A) and 3D scanner (B)

Then, the tooth was prepared for crown placement. The preparation used in this study was the one used for the metal-ceramic crowns (1.2 mm preparation at the buccal surface and 0.5 mm at the palatal surface). Next, root canal preparation was done. To prepare the tooth for an appropriate post, Gates-Glidden bur #2 and peeso reamers #2 and 3 were used; the remaining gutta-percha in the tooth canal was 4mm. The canal was prepared so that one-third of the root diameter would be on each side of the post space and a minimum of 1 mm dentinal tissue would remain from each side of the post. In this study, three post lengths (11, 13, and 15mm) were used.

The prepared surface was polished by Matic software. An attempt was made to make the geometry of the model similar to that of a real tooth as much as possible. Next, the tooth crown was removed from the height of 10 mm and used as the initial model of the metal-ceramic crown. The geometry of the post was designed by the Solid Work-2016 software and fed into the model (Fig. 2).

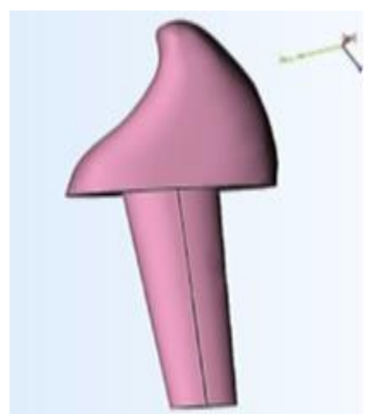

Fig. 2. Post and core model designed by Solid Work software

The access cavity was made by placing the post in the center of the canal. Gutta-percha was also molded by cones with a tip diameter of 0.35mm and 6% taper and placed 4mm from the apex. A 0.35mm coating was created around the root for the PDL. Finally, to simulate bone structure, a 2×2×2cm block with 2mm diameter was designed from a cortical bone filled with cancellous bone (Fig. 3).

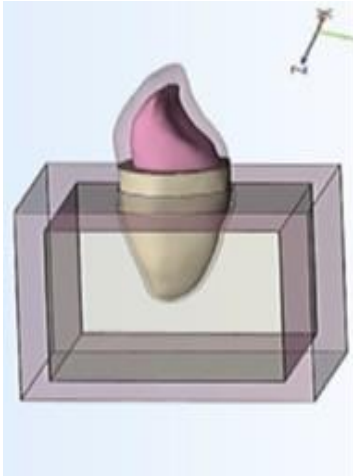

Fig .3. Final tooth model designed by Solid Work software

In the Abaqus-2018 software for finite element analysis, a friction-free contact between gutta-percha and the rest of the materials, contact with a coefficient of friction of 0.5 between the post and root, and contact with complete adhesion between the rest of the elements were modeled. The visco-hyperelastic constitutive model was linearly used for all elements except PDL. To simulate the complex behavior of the PDL, the underlying surface of the model was fixed, and a 300N force was applied to the crown at an angle of 135°. Due to the complex geometry of the model, four-sided pyramidal elements were used. Based on the independent analysis of the dimensions of elements, the number of elements of each model was selected to be about 45000. In the end, the models produced were analyzed by nonlinear finite elements, and maximum stress and strain were recorded.

RESULTS

Effect of ferrule height on the maximum stress and strain of root

Considering a ferrule height of 0 and a force of 300N at 135°, we investigated stress and strain (Fig. 4). The maximum and minimum stresses are shown with red and blue colors respectively. The maximum stress of 60.11Mpa was found in the buccal coronal one-third of the root. The amount of stress was reduced with movement towards the inner surface of the tooth. A maximum strain of 0.2904Mpa was observed in the palatal cervical one-third of the root

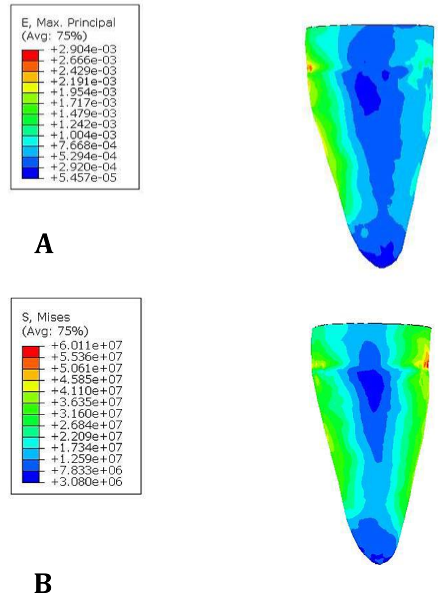

Fig. 4. Strain (A) and stress (B) at 0mm ferrule height

Considering the ferrule height of 0.5mm (Fig. 5), the maximum strain was 42.30Mpa at the coronal one-third of the root at the palatal surface and the maximum stress of 64.73Mpa was found in the coronal one-third of the root at the buccal surface. The amount of stress was reduced by moving towards the inner surface of the tooth.

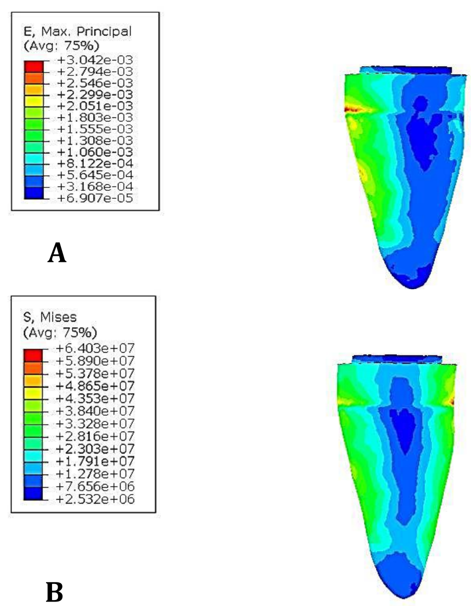

Fig. 5. Strain (A) and stress (B) at 0.5mm ferrule height

The strain and stress for the 1mm ferrule height were 66.69Mpa and 0.3137Mpa at the buccal coronal one-third and the palatal cervical one-third of the root, respectively (Fig. 6).

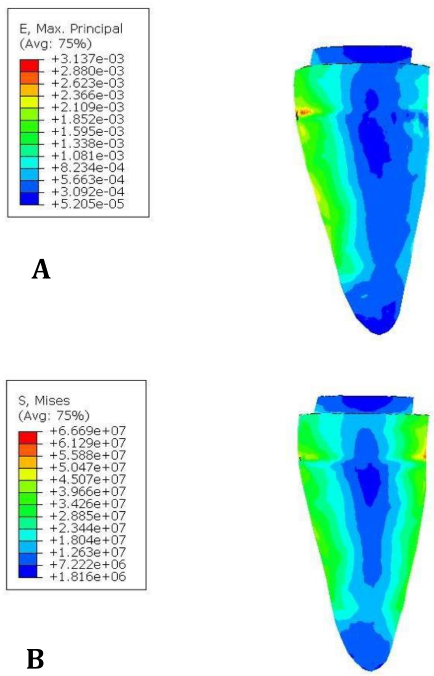

Fig. 6. Strain (A) and Stress (B) at 1mm ferrule height

For the 1.5mm ferrule height, the maximum stress was 72.79Mpa at the coronal one-third of the root on the buccal surface and the maximum strain was 99.31Mpa at the cervical one-third of the root on the palatal surface (Fig. 7).
Considering the 2mm ferrule height, the maximum stress was 72.18Mpa at the buccal surface of the coronal one-third of the root and the maximum strain was 0.3272Mpa at the palatal cervical one-third of the root (Fig. 8).
As for the 2 and 2.5mm ferrule heights on the buccal surface, the maximum stress was 75.44Mpa at the coronal one-third of the root on the buccal surface of the tooth. The maximum strain was 0.3317Mpa at the cervical one-third of the root on the palatal surface of the tooth (Fig. 9).
Considering the 5mm ferrule height on the buccal surface and 2mm ferrule height on the palatal surface, the maximum stress was 75.44 Mpa at the coronal one-third of the root on the buccal surface of the tooth. As expected, the amount of stress was higher on the palatal surface of the tooth due to a lower ferrule height. The maximum strain was 0.3236Mpa at the cervical one-third of the root on the palatal surface of the tooth (Fig. 10).

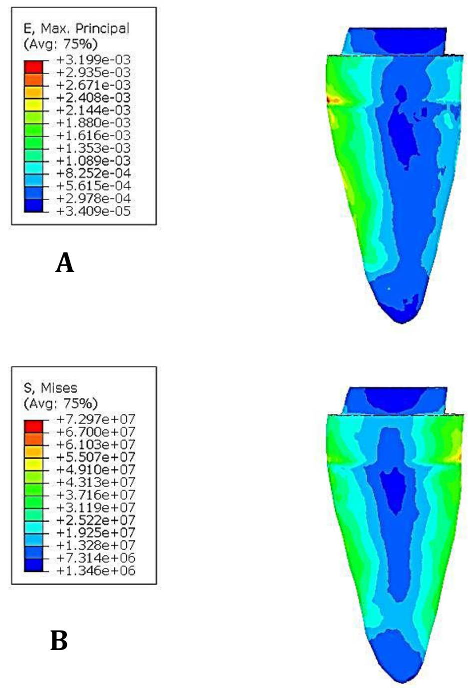

Fig. 7. Strain (A) and stress at 1.5mm (B) ferrule height

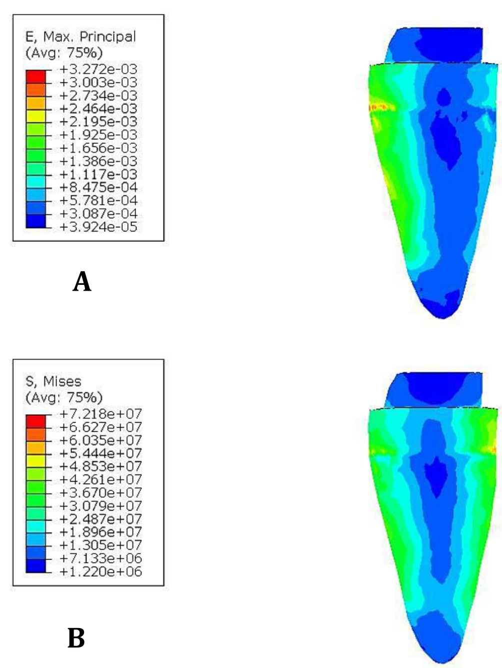

Fig. 8. Strain (A) and stress (B) at 2mm ferrule height

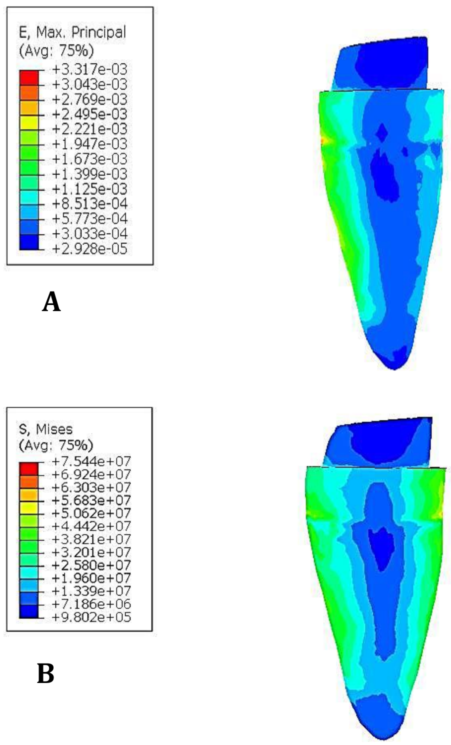

Fig. 9. Strain (A) and stress (B) at 2 and 2.5mm ferrule heights

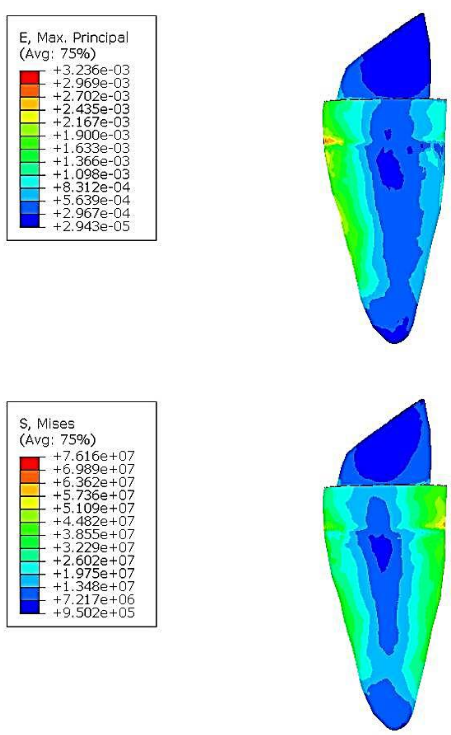

Fig. 18. Strain (A) and stress (B) at 2 and 5mm ferrule heights

Effect of post length on the stress and strain applied to the root

According to the results, the higher was the post height, the lower was the maximum stress applied to the root and the higher was the maximum strain applied to the tooth (Table 1).

Table 1. Effect of different post lengths on the stress and strain applied to the root

No	Post length (mm)	Maximum stress (Mpa)	Maximum strain (%)
1	11	76.16	0.32
2	13	72.91	0.33
3	15	71.85	0.34

Effect of ferrule height on the stress and strain applied to the post

Post stress was reduced with a rise in the ferrule height, but strain remained at approximately 0.08%. Stress values were 21.81, 21.83, 22.22, 20.04, 20.73, 20.68, and 20.46Mpa for 0, 0.5, 1, 1.5, 2, 2-2.5, and 2-5mm ferrule heights, respectively,

Effect of the force angle on the maximum stress and strain applied to the root

The results showed when the force was applied to the tooth vertically, the maximum stress was 15.69Mpa and the maximum strain was 0.0524Mpa. Further, when the force was applied horizontally, the maximum stress applied to the tooth was 101.8Mpa and the maximum strain was 0.5271Mpa. When the force was applied obliquely, the maximum stress was 76.16Mpa and the maximum strain was 0.3236Mpa. The results showed the higher was the angle of force applied, the higher were the maximum stress and maximum strain in the root.

Effect of the force site on the maximum stress and strain applied to the root

When the force was applied to the incisal edge, the maximum stress applied to the tooth was 76.16Mpa and the maximum strain was 0.3236Mpa. When the force was applied to the cingulum area, the maximum stress applied to the tooth was 33.61Mpa and the maximum strain was 0.118Mpa. The closer was the location of force to the incisal edge, the higher was the maximum stress and strain.

DISCUSSION

Many factors are involved in the fracture resistance of the severely damaged teeth. Some factors affecting the strength include the presence of ferrule, ferrule height, amount of force, applied force, angle of force applied to the tooth, and location of force application, the most important of which is the ferrule. The present study investigated the effect of these factors.

An important point in tooth preparation for crown placement is adequate coronal tissue. Various factors are involved in stress distribution and fracture resistance in severely damaged teeth reconstructed with post and core. One of these factors is the remaining tooth tissue above the ferrule.

The results of this study showed the maximum stress and strain increased in the tooth and decreased in the post with an increase in the FCR (Tables 1). Further, the maximum stress and strain created in the dental model increased with a rise in FCR, indicating that the minimum ferrule height required for tooth fracture resistance against the applied forces was 20% (2mm). The amount of stress and strain reduced when the ferrule height increased to 1.5mm (FCR=15%), but no change occurred in the stress and strain when the ferrule height increased above 2mm. On the other hand, the amount of stress and strain decreased when the ferrule height was above 2mm because, due to the morphology of the central teeth, the buccal wall height was increased.

Different studies have reported similar results in this regard. This effect of ferrule height was in line with the results of Eraslan et al [21], indicating that a 2mm ferrule exerted a lower force on the tooth than a 1 mm ferrule or 0mm ferrule. The results of Dikbas et al [18] and Mahdavi Izadi et al [20], confirm this result. Maintaining the ferrule height of 1.5-2mm significantly increases the strength and fracture resistance of endodontically treated teeth [22-26]. An important point to consider in interpreting the results of various studies in this regard is that the results of studies who's modeling merely involves post and core and uncrowned teeth are not comparable with those which have investigated crown in their modeling because ferrule makes sense with crown, and if the crown is not evaluated, the increase of ferrule can only alter the post length.

A difference between this study and other studies was the use of FCR. In other studies, only ferrule height was evaluated, while the height of teeth varies in different individuals, especially those who suffer from gingival and bone resorption. On the other hand, treatments such as surgery increase the crown length. Different studies have indicated that stress in the root is associated with the post length. On the other hand, shorter posts cause more stress concentration. In this study, the effect of post length on the stress and strain applied to the tooth showed the maximum stress applied to the tooth increased with a rise in the post length.

Al-Omiri et al. [27] and Kainose et al. [28] reported that the reduced post length decreased the stress applied to the cervical region of the tooth and increased the stress at the end of the root. Accordingly, the increased ferrule height prevents the wedging forces on the apical areas of the root due to the conical post (as mentioned in the above studies).

The angle of force applied to the tooth model indicated the closer the force application angle to the horizontal position, the higher would be the maximum stress and strain. On the other hand, the application of longitudinal forces increased the fracture resistance compared to the angular forces. These results were in agreement with those of Al-Omiri et al., [27] indicating that horizontal forces exerted more stress to the tooth in the cervical area than the vertical forces. The forces applied longitudinally make the crown adapted better on the prepared tooth, while the angular forces cause tensile and shear stress on the cement-crown interface, dental cement, and cement itself. If these stresses are increased beyond a certain level, the post is displaced in the root and the torque of the forces created will elevate the wedging effects.

Analysis of the location of the force indicated that when the force was applied to the incisal edge of the tooth, the maximum stress and strain created in the tooth were elevated and when the force was applied to the cingulum region, these values decreased. Considering the mechanism of lever type I, when the length of the actuator arm is increased (incisalization of the force site), the mechanical advantage of this lever is increased. On the other hand, more stress will occur at the end of the lever (more apical areas) when less force is applied. Therefore, in patients where the occlusal contacts of the anterior teeth are more incisal, the possibility of post and core failure is higher; hence, other measures should be adopted to reduce and cope with this effect. However, it should be noted that the length of the contact during eccentric movements is increased when the occlusal contact point becomes more cervical, which in turn exposes the tooth to a longer effect of occlusal forces.

Despite our findings, our method (final element analysis) was a limitation and occlusal type of patients was not considered in this study. More recent restorative material, such as zirconia crowns, may be evaluated [29]. Thus, further clinical and experimental studies are required to investigate this issue.

CONCLUSION

Within the limitations of this study, it can be concluded that increasing the FCR elevates the tooth fracture resistance against the applied forces. Increasing the ferrule height to 2mm (FCR=20%) greatly elevates the tooth fracture resistance, but it has a lower effect beyond this level. When the force angle is more horizontal and the post length is reduced, the stress and strain applied to the tooth are elevated. Due to the synergistic effect of ferrule height and post length, in the presence of a tall ferrule height, a shorter post length can bring about successful treatments. When the force site is more incisal, the stress applied to the root is also increased.

CONFLICT OF INTEREST STATEMENT

None declared.

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