

Design and Finite Element Analysis of a New Custom Made Orthotropic Post Material for Dental Applications

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Citation

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Abstract

The aim of this work was to conduct a parametric study of the stress distribution of endodontically treated dental post and core of a central maxillary incisor, and to suggest a new post material which minimizes the chances of post debonding from the dentin.

Three different post materials (two references and one made in our laboratory) have been analysed with finite element simulations, and compared stress distributions under loading conditions. The dentin-cement-post interfacial stresses have been evaluated to study the debonding phenomena of the dental post.

From the study of 3 different posts, it was found that our new orthotropic glass post generates lower stresses than the titanium post for endodontically treated tooth. From the analysis of three different horizontal loading planes, it was found that the stress distribution is most sensitive to the applied load when the load is applied at the mid section of the crown. It has been found that post cement interfacial stress increases with increase in modulus of the post.

For the integrated post and core made from the same material, our results suggest that the modulus of the post material should be as close as the modulus of the dentin at the apical part and as close as crown at the coronal part of the post to minimize the chance of interfacial debonding and enhance the reliability of dental post. It has been observed, from our simulations, that the modulus of the post is most important than either the post is isotropic or orthotropic.

INTRODUCTION

Different metallic and non-metallic materials – gold, titanium, stainless steel, fibre reinforced composites, etc – are being used for dental posts in restoring the endodontically treated tooth to provide retention to the core that replaces lost coronal (region below the crown of the tooth) tooth structure. Recent development of “gum metal” (super elastic titanium alloy) [1] has provide a competition for the composite material in the biomedical applications, however, it has not been noted in a dental post.

The contact surfaces between the dentin and the cement, and cement and post are called the dentin-cement interface, and cement-post interface respectively. The dentin-cement-post interface infers two interfacial surfaces consisting of dentin-cement and cement-post.

A dental post should stabilize the core and not weaken the root [2]. An ideal dental post should have high stiffness at the coronal region and this stiffness gradually reduces to the value of dentine at the apical (apex/bottom of the tooth) end [3]. The stiffness mismatch between intraradicular (different

tissue layers of the tooth structure) devices and dental tissues will result in large stress concentration at the restorative materials/tooth interfaces [4]. Different materials have different load bearing and dissipation properties, as a result, restorative materials play an essential role in the success of restoration [5].

Finite element simulation has been used [3,4,5,6,7,8] to analyse the stress distribution on restored teeth and posts with different post materials. In dental applications, glass fiber posts are reported to be superior to the stiff posts like, gold, stainless steel and ceramic posts [3,6,7,8]. This is due to the fact that the glass fiber posts have modulus closer to dentin. The parallel fibers used in the fiber reinforced posts can absorb and dissipate the generated stresses. It has been observed that the post related factors (modulus of elasticity, diameter and length) influence the stress fields inside the post [3,6] but the maximum stress values in the restored tooth system are rather insensitive to post materials [4]. There is also an argument that the core material has greater impact on the stress distribution of the post than that of post material and size [9].

The direction of the functional load has a great effect on the maximum stress and displacements [9,10,11]. The horizontal loading generates larger bending moment than the vertical loading, as a result, horizontal loading yields larger stresses than the vertical loading.

The modulus (stiffness) mismatch of the adjacent parts, particularly at the post and cement, and cement and dentin interfaces, is considered to be the weakest interface in the restored tooth. These interfacial surfaces are the probable debonding surfaces. Also, it has been observed that large von Mises stresses are generated at the post-cement interface on the restored tooth [4,7,8]. The stress concentration at this interface increases the probability of debonding failure. Therefore, recent studies [3,4,8] are focusing on the importance of the interface stresses. In regard to this, Fujihara et al. [3] introduced functionally graded composite dental post, whose stiffness varies along the length of the post. This is one step further than the conventional thinking of an ideal post, which states that the post modulus should closely match with the dentin modulus [4]. The gradual reduction in modulus mismatch of the functionally graded post results in reduction of the peak tensile and shear stresses at the post-cement interface as compared to the stainless steel post. A very few studies have systematically focused on the effects of post materials on stress concentration at the post-cement interface, which is very important to understand the debonding behaviour of the post. The knowledge of the interfacial stresses yielded by different post materials provides better selection of the post materials.

The objective of the present work was to evaluate the stress distribution of a new polymeric composite (orthotropic) post, made in our laboratory, using averaged tooth geometry [4,12] under different loading conditions through three dimensional finite element simulations. The stress distributions of the laboratory made post were compared with two different post materials – isotropic titanium post and the orthotropic post reported in [8]. The effect of loading planes for the horizontal loading conditions was also studied. Different post materials were simulated to study the post-cement interface stresses to determine an efficient post for the dental restorations. The work suggests the location of debonding initiation based on the magnitude of stress concentration at the post-cement interface

MATERIALS AND METHODS

POST MATERIAL

The glass fiber post material was developed in our laboratory. The CYD-128 is diglycidyl ether of bisphenol resin with an average molecular weight of 385 g/mol. Aromatic hardener (JHB-590) has an acid value of 660 – 685 mgKOH/g. Nanometer-sized sepiolite particles were obtained from Shaanxi Institute of Mining, China. Sepiolite particles were washed using a dilute HCl solution and then with distilled water. The clean samples were dried in an oven. After cooled down to room temperature, these sepiolite particles were stored in a desiccator. Blending was carried out in a Haake mixer followed by an hour ultrasonic treatment in order to gain uniform dispersion of sepiolite fillers. The mixing temperature was 130oC. Hardener (epoxy: hardener = 1:0.875) was then added to the mixture as its temperature was lowered. Unidirectional S-glass fiber was used as the reinforced fibers. The flexural properties were measured using a universal testing machine following ASTM-D790. ASTM-D256 Ten specimens for each test were examined. The mean values and their standard deviations were calculated. The impact tests were performed at room temperature using an impact tester (XCJ-400) following ASTM-D256. Table 1 shows the mechanical properties of the composite material made in our laboratory. The proposed post is an orthotropic post so it has a uniform modulus of 44 GPa along the longitudinal direction and 3.6 GPa along the transverse direction.

Figure 1

Table 1: Mechanical properties of composite.

Mechanical Properties	Sepiolite content, wt%	
	0	1
Flexural strength, MPa	63.57	125.71
Flexural modulus, GPa	42	44
Impact strength, kJ/m ²	4.1	20.92

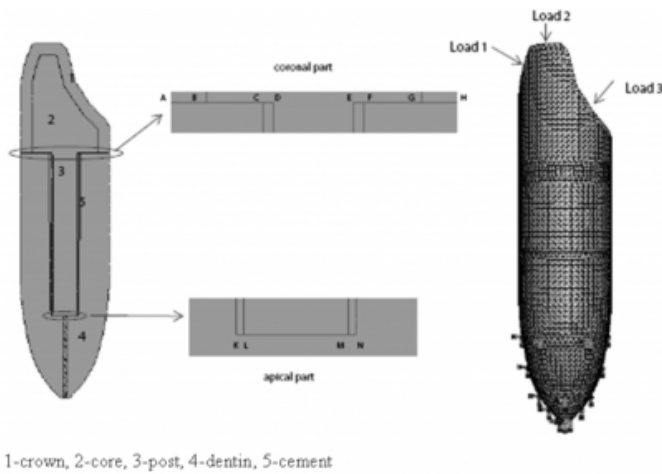
FINITE ELEMENT MODELING

Figure 1 shows shape and dimension of the tooth, which were taken as an average from the literatures [4,12]. The model consists of post, core, crown, cement and dentin. Since the modeled tooth consists of a prefabricated post, a varying thickness of cement was considered to fix the post. For simplicity, the thickness of the cement was assumed to vary linearly from 0.2 to 0.1 mm from top to bottom. Table 2

shows the assigned material properties of the model.

Figure 2

Figure 1: Load and boundary conditions.



1-crown, 2-core, 3-post, 4-dentin, 5-cement

Path key points	Distance, mm	Remarks
AB = GH	0.71	crown thickness
BC = FG	1.05	part of core
CD = EF	0.2	cement thickness
DE	1.5	post diameter
KL = MN	0.1	cement thickness
Height of crown	7	
Height of post	10	
Height of dentin	15.1	

Figure 3

Table 2a: Material properties of isotropic post. The properties are taken from [1].

Part	Young's Modulus (MPa)	Poisson's ratio
Crown (porcelain)	120,000	0.28
Titanium post	116,000	0.33
Cement	22,000	0.35
Dentin	18,300	0.27
Core	12,000	0.33

Figure 4

Table 2b: Material properties of the orthotropic posts. The properties of the reference glass post are taken from [1].

Property	Post made in our lab	Reference glass post
E_x (GPa)	44	37
E_y (GPa)	3.6	9.5
E_z (GPa)	3.6	9.5
ν_{xy}	0.25	0.27
ν_{yz}	0.25	0.34
ν_{xz}	0.28	0.27
G_{xy} (GPa)	4.2	3.10
G_{yz} (GPa)	4.2	3.50
G_{xz} (GPa)	1.5	3.10

The geometrically complicated crown, core, cement, post and dentin were modeled with Abaqus 6.5 [13]. The model has 122206 elements. Due to complicated geometries of the models, free meshing technique [13] was followed and tetrahedral elements were adopted to discrete the parts, and to achieve the convergence. It was suggested that the four node first order linear tetrahedral solid elements, C3D4, which were used for the stress analysis, should be used with fine meshes to obtain the accurate results because the constant stress tetrahedral elements exhibit slow convergence [13]. Therefore, fine meshes were assigned to the elements. The simulations were performed on Pentium 4 personal computer of 3.0 GHz CPU speed and 1 GB memory. Due to the large number of elements, the average calculation time was 17 minutes.

The materials used for the modeling tooth parts, except the post which was orthotropic, were assumed to be linearly elastic, isotropic and homogeneous. However, to study the effect of interfacial stresses, the titanium post (isotropic) was also simulated. The different adjacent parts were tied together with the surface to surface contact (TIE constraint in Abaqus) to simulate the tooth as a single unit, in other words, the displacement was continuous. The master – slave type contact conditions were defined at the interfaces without friction. As a boundary condition no translational and rotational displacements were allowed for the outer nodes on the bottom part (below the apical part of the post) of the model (Figure 1).

In this research, the horizontal bruxism, vertical bruxism and mastication loads were simulated with – 16 N load (load 1), 100 N load acting on vertical direction (load 2) and 100 N load acting at 55° oblique with reference to the horizontal axis (load 3), respectively. The load and boundary conditions are shown in Figure 1. The applied loads were chosen and interpreted on the basis of [4,9,14]. The loads were step type loads. All the forces were applied on the respective portion of the geometry as distributed pressure. For analyzing the stress distributions in the restored tooth, three dimensional static finite element analysis simulations were performed.

The von Mises stress was used to evaluate the generated stresses during simulations. The stress distribution was also evaluated along the apical and coronal cross-sections of the post and on the surface along the post at the post-cement interface, which is a probable debonding zone. For the cross-section evaluation, the abscissa of the plot starts from the left hand outside of the root and at the interface evaluation, the abscissa of the plot starts from the apex of the post.

RESULTS

STRESS COMPARISON FOR DIFFERENT LOADING CONDITIONS

Figure 2 shows the von Mises stress distribution on the restored tooth (with orthotropic posts) for vertical bruxism and mastication. In vertical bruxism, the maximum stress distribution inside the post is observed at the interface of the post and cement on the loading side. Though the magnitudes of the load are equal on vertical bruxism and mastication, the stresses are larger on the mastication. In mastication, the maximum stresses are generated on the post at the interface of the post and cement at the lower half part, which can be attributed to the bending of the post inside the rigid structure.

Figure 5

Figure 2: Contour plots of the von Mises stress distributions in MPa for bruxism and mastication (orthotropic post, $E_x = 44 \text{ GPa}$).

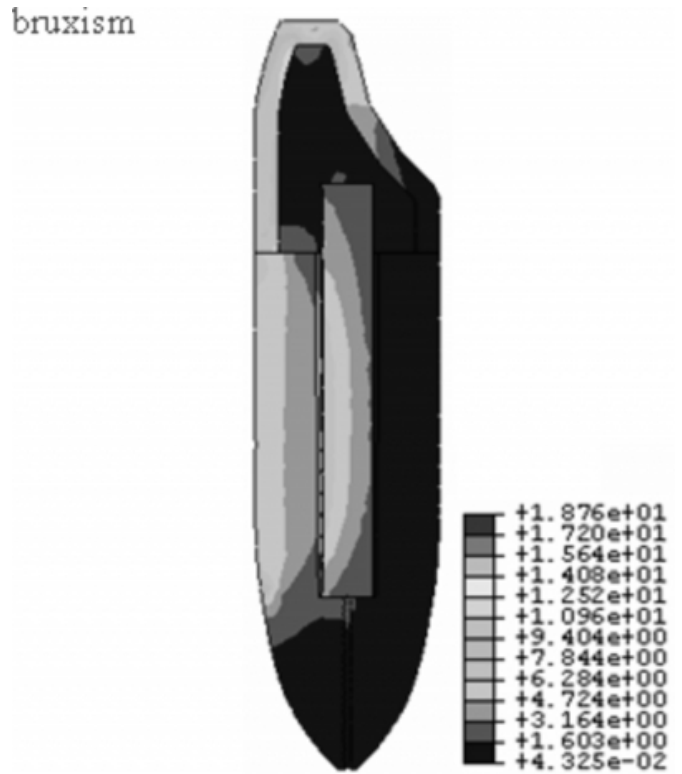
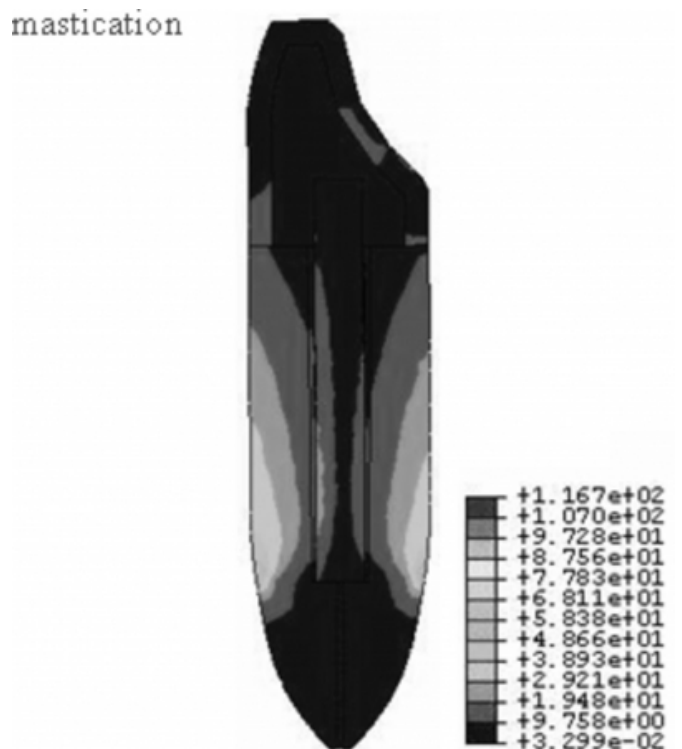


Figure 6



Three different horizontal bruxism areas – top inclined, middle layer and lower layer (Figure 3) – were considered to study the effects of loading areas on the stress distribution on crown, core, post and dentin. In this study, the magnitude of the load was kept constant for the three loading conditions. It is worth noting that, two loading types (middle and lower layers) are perfectly horizontal whereas the top inclined is not perfectly horizontal. Instead, it is at 85° with respect to abscissa, which facilitates a vertical pressure on the inclined loading area. In other words, a part of the top inclined horizontal load contributes to the vertical loading. The middle layer horizontal bruxism area yields maximum stresses in the restored tooth except on crown and core. The top inclined loading generates larger stresses on crown and core. Since, we are analysing the post (orthotropic) and the middle layer horizontal bruxism generates larger stresses in the post (table 3), henceforth, the simulations and analysis are performed with the middle layer horizontal bruxism.

Figure 7

Figure 3: Different loading areas on crown.

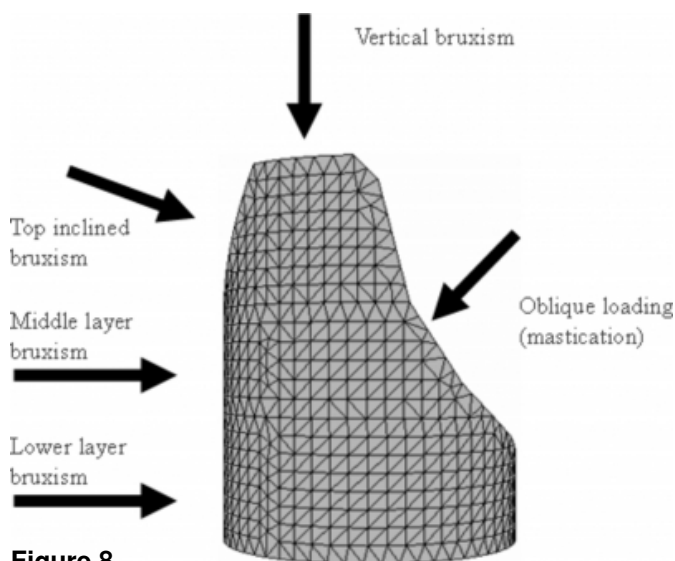


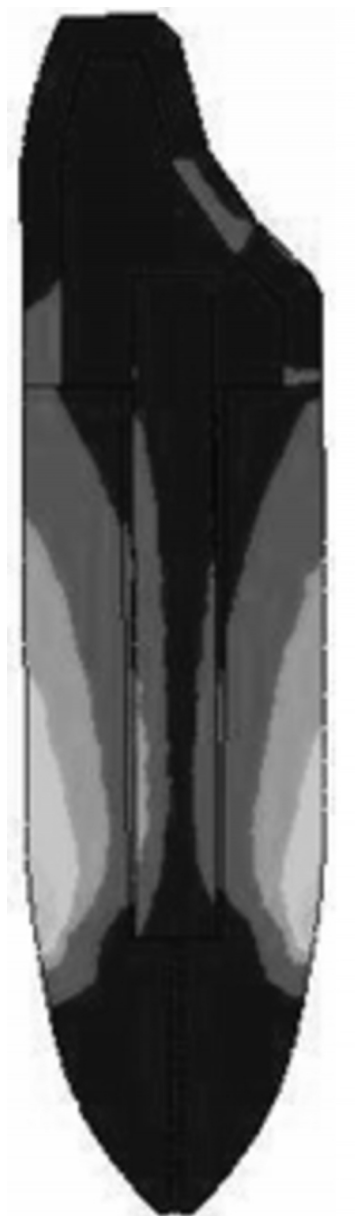
Figure 8

Table 3: Comparison of stress distribution on crown (120 GPa, $\nu = 0.28$), core (12 GPa, $\nu = 0.33$), post (our orthotropic post, table 2b) and dentin (18.3 GPa, $\nu = 0.27$) during three different horizontal loadings.

Loading region	Maximum von Mises Stress, MPa			
	Crown	Core	Post	Dentin
Top inclined	10.72	1.207	5.459	21.77
Middle layer	9.4	1.165	6.161	26.78
Lower layer	7.113	1.096	4.609	22.86

Figure 9

Figure 4: Contour plots of the von Mises stress distribution in MPa for horizontal loading (orthotropic post, Ex = 44 GPa).



S, Mises

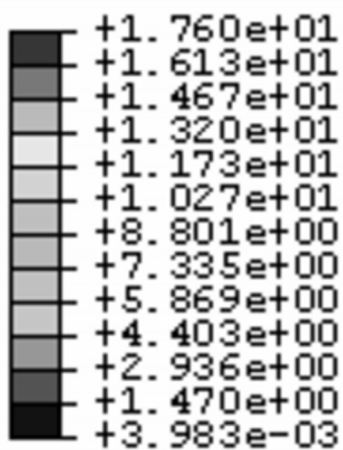


Figure 4 shows the von Mises stress distribution on the restored tooth, and post and core for horizontal bruxism. The horizontal bruxism load was applied on the middle layer of the crown (Figure 3). The horizontal load bends the system towards the opposite side. The surface (post-cement interface) of the post has maximum stresses. This is because of change in stiffness of the parts across the interfaces and the tie constrain defined along the interfaces.

Though the von Mises stress lacks the sign of the stresses (i.e., tensile and compression components), it is helpful in comparing maximum stress generated at the interfaces. So, the graphical comparisons were performed with the von Mises stress. It is worth mentioning that tensile and shear stresses at the interfaces would give a better characterization.

COMPARISON OF POST MATERIALS

Table 4 shows a comparison of stress distributions among three different posts for different loading conditions. In these simulations, the horizontal bruxism load was applied on the middle part of the crown (Figure 3). The modulus of our post was 44 GPa in the longitudinal direction, which was slightly larger than the elastic modulus of the reference post (37 GPa). As a result, the composite post produced in our laboratory shows relatively large interface stresses than the reference composite post. The titanium post, which has largest elastic modulus among three post moduli, generates largest stresses.

Figure 10

Table 4: Comparison of stress distribution on posts (titanium and two different orthotropic) under three different loading conditions

Type of Loadings	von Mises Stress, MPa			MPS1, MPa			MPS3, MPa		
	Ti-post	Post*	Our post	Ti-post	Post*	Our post	Ti-post	Post*	Our post
Horizontal	15.74	5.16	6.16	15.07	4.57	5.72	1.20	0.30	0.15
mastication	70.87	21.74	25.72	67.11	18.63	21.89	3.33	1.00	0.55
bruzims	16.72	6.46	7.55	3.03	0.93	0.88	-1.2	-1.27	-1.22

* - Reference Orthotropic Glass Post reported in [10], MPS1-Maximum Principal Stress, MPS3-Minimum Principal Stress

INTERFACE STRESSES

Isotropic and orthotropic posts of different moduli of elasticity were simulated to understand the stresses generated at the interface of the adjoining materials, particularly at the interfaces of core and crown, and post and cement. The investigations were performed at apical and coronal parts of posts. Four different materials having modulus – 15, 18.3, 44 and 116 GPa respectively – were

studied to represent a wide variety of isotropic posts. The post materials of 15, 18.3, 44 and 116 GPa represent the post softer than dentin, the post similar to dentin, the post slightly larger modulus than dentin and the titanium post, respectively. Figure 5 shows the von Mises stress distributions on the restored tooth with isotropic posts for middle layer horizontal bruxisms. It can be observed that due to the modulus mismatch between the dentin and the post, the interface stresses are larger on both sides of the post. The isotropic post of modulus 116 GPa yields larger stresses at the interface of the post and dentin. Similarly, Figure 6 shows the stress distributions on the restored tooth with orthotropic posts during middle layer horizontal bruxisms. The observation for different orthotropic posts is similar to the above explained isotropic post. The maximum stress generated on isotropic post is identical to that of orthotropic post.

Figure 11

Figure 5: The von Mises stress distributions on restored tooth at the apical cross-section with the isotropic posts of different moduli - 15, 18.3, 44, and 116 GPa. (post and core same material). The dotted oval shows the location of maximum interface stresses at the post-cement-dentin interface.

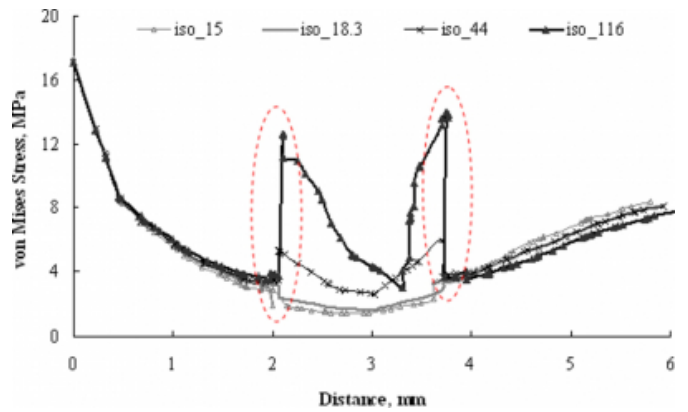


Figure 12

Figure 6: The von Mises stress distributions on restored tooth at the apical cross-section with the orthotropic posts of different moduli - 15, 18.3, 44 and 118 GPa (post and core same material). The dotted oval shows the location of maximum interface stresses at the post-cement-dentin interface.

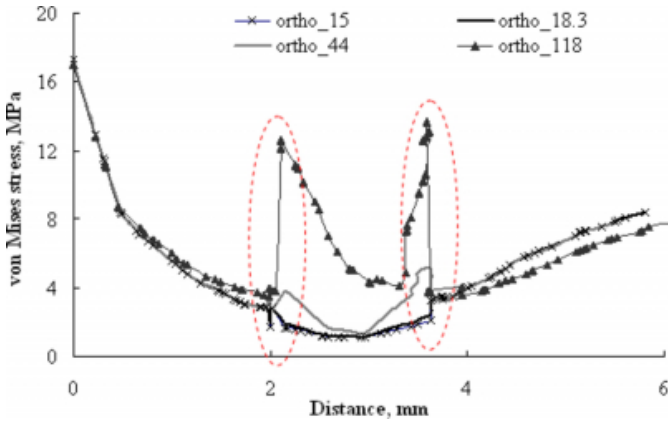


Figure 13

Figure 7: The von Mises stress distributions on restored tooth at the coronal cross-section with the isotropic posts of different moduli - 18.3, 44, 116 and 120 GPa (post and core same material). The dotted oval shows the location of maximum interface stresses at the core-crown interface.

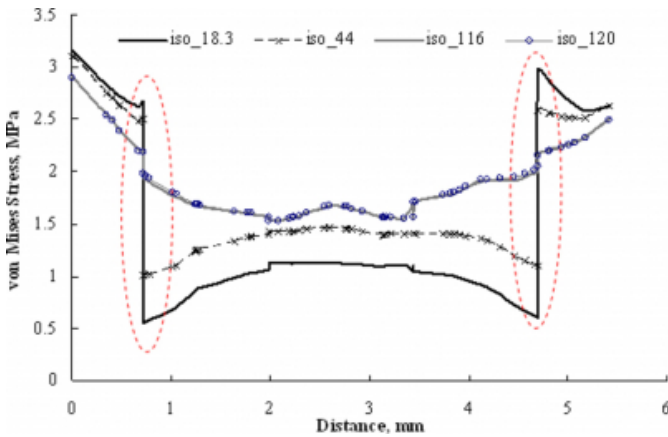
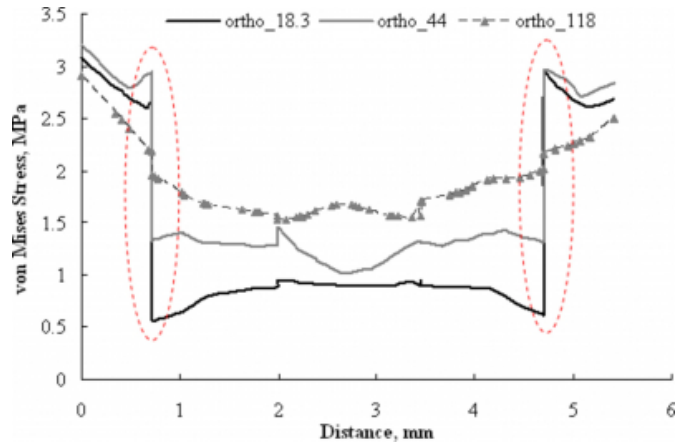


Figure 7 shows the von Mises stress distributions on the restored tooth for middle layer horizontal bruxisms at coronal part with isotropic posts. The integrated post and core were assigned same elastic modulus in order to focus on the effect of the modulus mismatch between post-core and crown. It is observed that because of the higher core-crown modulus mismatch, a large jump on the stress levels occurs at the interface of the core and the crown. In addition, the smaller the difference in modulus between the crown and the core, the smaller the jump on the stress level at the interface. Similarly, Figure 8 shows the stress distributions on the

restored tooth during middle layer horizontal bruxisms at coronal part of orthotropic posts. The observation is similar to the isotropic post. The maximum stress generated on the isotropic posts is identical to that of orthotropic posts.

Figure 14

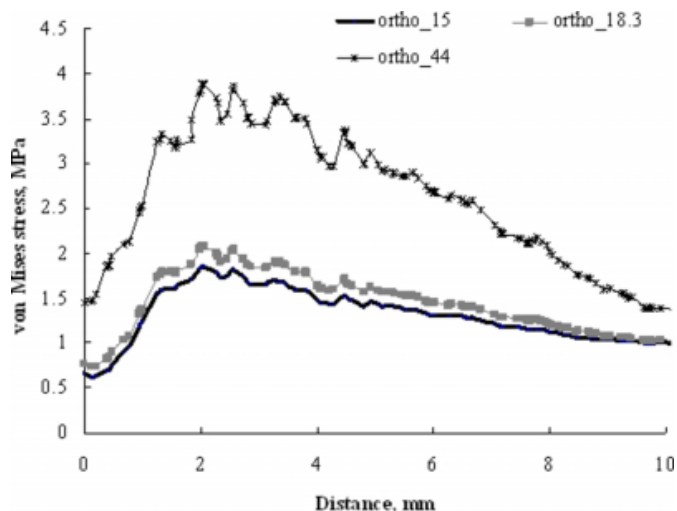
Figure 8: The von Mises stress distributions on restored tooth at the coronal cross-section with the orthotropic posts of different moduli - 18.3, 44 and 118 GPa (post and core same material). The dotted oval shows the location of maximum interface stresses at the core-crown interface.



It is reported that debonding of post occurs at the post - cement interface [3,4], hence, the stress distribution along the surface of the post at the post-cement interface has been noted. Figure 9 shows the von Mises stress generated along the outer surface of the post at the post-cement interface during middle layer horizontal bruxism. Distances in Figure 9 are measured from the apex of the post to its coronal region (crown) along the longitudinal axis. The stress uniformly increases from apex to its maximum value, located at 2.2 – 2.3 mm from the post apex, and then it decreases.

Figure 15

Figure 9: The von Mises stress distributions on the surface of the posts at the post-cement interface. The orthotropic posts have modulus of 15, 18.3 and 44 GPa. The abscissa shows the length of the post starting from the apex of the post to its coronal region.



DISCUSSION

ANALYSIS OF STRESS DISTRIBUTION UNDER DIFFERENT LOADING CONDITIONS

During vertical bruxism, maximum stress distribution at the interface of the post-cement on the loading side (as can be seen in Figure 2) is attributed to the bending of the post. The bending of the post is restricted by a rigid structure of the dentin. Similarly, maximum stresses are observed at the post-cement interface for mastication but on the opposite side of the loading. On the horizontal bruxism, due to the bending, the larger stresses are developed on the post at the post-cement interface. The significant bending of the restored tooth may be considered as a beam clamped into the cortical bone cavity. Though the applied load is very small (16 N) in horizontal bruxism as compared to other two cases (100 N), relative stresses generated on the restored tooth are larger under small horizontal bruxism.

The distance between the load application area and the lower fixed part of the root influences the stress distributions within the post, notably during horizontal bruxisms. Yaman et al. [9] also noted that the loading region affects the stress generation. In this research, three different loading areas were considered during horizontal bruxisms. In case of the top inclined bruxism, a part of the applied load contributes to the vertical load as a result the resultant horizontal load will be smaller than the applied load. In the other two cases (middle and lower layers) the applied load acts perpendicular

to the loading plane, hence there is no contribution to the vertical loading and is perfectly horizontal.

The tabulated (table 3) von Mises stress shows that the middle layer horizontal bruxism generates largest stresses at the interface of post and dentin. The middle layer bruxism generates larger bending moment on the post and the dentin than other two types of horizontal loadings. This suggests that the loading plane governs the stress distributions during horizontal loadings. The loading area should be considered while comparing the results reported in different papers. Therefore, to evaluate and analyze the critical stresses, it is preferable to apply the load on the middle part of the crown, which is more detrimental to the applied load.

EFFECT OF POST MATERIALS

Table 4 shows that the titanium post yields larger stresses than the other two fibre reinforced composite posts. Except the post materials, the properties of the other parts were same. This suggests that the use of new composite posts are preferable than the stiff posts, like titanium. The titanium post generates more than three times larger interface stresses than the composite posts (table 4) under the same initial and boundary conditions. This is due to high modulus of the titanium post as compared to the orthotropic posts. This strengthens the fact that the modulus of the post governs the interface stress generated within the post, and therefore, the reliability of the dental post system. In other words, the post-cement interfacial stress increases with increase in modulus of the post.

ANALYSIS OF INTERFACE STRESSES

The modulus mismatch between the post-core and the dentin results in large stresses (concentrations) at the interfaces. If the adjoining parts have similar stiffness with each other, a continuous stress distribution is more likely across the interface. Figure 5 and Figure 6 show the effects of post materials on stress distributions at the post-cement interface. The posts (44 GPa and 116 GPa) which have larger stiffness than the dentin (18.3 GPa), are showing large stress jump at the interface of the post-cement-dentin. On the other hand posts stiffness (15 GPa and 18.3 GPa) similar to the dentin are showing low stress jump at the interface of the post-cement-dentin, as a result there is almost continuous stress distributions across the interfaces. This infers that if the post has similar stiffness as of dentin in the apical region, then the stress concentration (jump) at the interfaces is less.

Similarly, Figure 7 and Figure 8 show that if the stiffness of

the crown is similar to the core-post then there will be continuous stress distributions across the interfaces. This will greatly minimize the tendency for interface debonding.

It has been observed from our simulations, a new finding, that the modulus of the post is most important than either the post is isotropic or orthotropic. This can be verified from the figures 5-8. The isotropic posts show identical interface stresses (maximum) as that of respective orthotropic posts (modulus along fiber direction) at the respective cross-sections (either apical or coronal). In other words, the modulus of the post is most important than either the post is isotropic or orthotropic.

Based on above observations, for the integrated post-core system made from the same material, it can be suggested that the ideal post-core combination should be the one which has stiffness similar to the crown at the coronal part and stiffness similar to the dentin at the apical part. In other words, the integrated post-core combination should have a gradient stiffness – maximum stiffness (similar to crown) at the coronal part and minimum stiffness (similar to dentin) at the apical part. This will minimize the chance of interfacial loosening and enhance the reliability of dental post.

From the Figure 5, it can be noted that an almost equal amount of stresses are developed on the outer edge of the dentin (start and end of the graphs). This suggests that the post material does not affect the overall stress distribution (maximum peak stresses) on the tooth except the stress distributions inside the post and along the post-cement interface. This is due to the geometry and boundary conditions of the tooth.

Debonding is one of the major causes of failure of the restoration. If we assume that debonding occurs at the post-cement interface due to the failure of the bonding agent, cement, then from the Figure 9 it can be suggested that the debonding starts from the lower half side of the post, where the maximum interface stress is generated. For example, under the simulated condition for the 10 mm long post, the debonding initiates at 2.2 - 2.3 mm from the apex of the post. As the stiffness of the post increases, maximum stresses on the surface of the post at the post-cement interface also increases.

In future, we plan to simulate the integrated post-core system, whose stiffness varies gradually. The integrated post core system will have the stiffness similar to the ceramic crown at the coronal region and the stiffness similar to the

dentin at the apical region. Also, the research will explore the possibility of producing gradually varying integrated post-core. The high stiffness takes the stress from the core and the gradual reduction of stiffness unloads the stress from the post to the dentin uniformly. The gradual unloading would eliminate stress concentration and reduce the interfacial shear stress [3].

CONCLUSIONS

This work conducted a parametric study of the stress distribution of endodontically treated dental post and core of a central maxillary incisor. A new orthotropic post material was developed in our laboratory. It was found that post cement interfacial stress increases with increase in modulus of the post. From the analysis of three different horizontal loading planes, it was found that the stress distribution is most sensitive to the applied load when the load is applied at the mid section of the crown. For the integrated post and core made from the same material, our results suggest that the modulus of the post material should be as close as the modulus of the dentin at the apical part and as close as crown at the coronal part of the post to minimize the chance of interfacial debonding and enhance the reliability of dental post. It was observed, from our simulations, that the modulus of the post is most important than either the post is isotropic or orthotropic.

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