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Comparison of the effect of thermal stresses on tooth-colored posts, cores and tooth structures by finite element analysis

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ABSTRACT

Objectives: The aims of this study were to analyze the influence of cold heat flow in all ceramic crown material, composite core, zirconium and glass fiber reinforced composite post materials, resin based luting cement and root dentin; and to compare these two tooth-colored post systems about their temperature and thermal stress distributions.

Materials and Methods: A 3-dimesional finite element model of maxillary left canine tooth was constructed. All ceramic crown, composite core, tooth dentin, post and bone were modeled. In the first part of this study, initial body temperature was assumed to be 36.5°C and the outer temperature was reduced to 0°C for 5 secs. In the second part, the thermal stress was calculated as a result of temperature change. For the analysis, 7 nodes of the finite element model were selected and heat flow, temperature and thermal stres on these nodes were evaluated.

Results: Mean temperature value was 15.75 °C for GFRC post model and 15.47 °C for Zr post model. The maximum von Mises stress was obtained at the node C in both post systems. In general, thermal stress was observed on the cervical part of all-ceramic crown and there was an interface between root dentin-composite core and post material. The temperature gradient of the GFRC post was smaller than that of the zirconia post.

Conclusions: Within the limitation of this study, zirconia posts produced greater stress than GFRC posts. Temperature changes had more effect on the post-cement interface and cervical areas than on the other areas.

Key words: Glass fiber-reinforced composite resin post, zirconia post, thermal stress, finite element method.

INTRODUCTION

Endodontically treated teeth with excessive loss of substance very often needs to be restored with a post and core in connection with the replacement of the missing coronal portion of the tooth to the remaining tooth structure. Thereby, the required retention and resistance to the final restoration are achieved.[1-3] Metal post and cores are widely used in clinical practice because of their superior physical properties. However, metallic restorations may cause allergic or toxic reactions within adjacent soft or hard dental tissues,[2] and corrosion products may deposit in the gingival tissues when nonprecious alloys are used.[3] In addition, metallic or dark posts or cores will be readily visible and may produce a gray discoloration of translucent all-ceramic crowns and the surrounding gingivae.[3] Due to the increasing demands on the esthetics of dental restorations and the biocompatibility of the materials used, tooth-colored, metal-free, post and core systems have been developed.[1,3]

Several tooth-colored post and core systems are presently available, including zirconia ceramics and glass fiber systems that have certain advantages over metal alloys.[3] Zirconia posts exhibit high flexural strength and fracture toughness, aside from that they can be silanated and bonded with resin luting agents.[4,5] Additionally, they are biocompatible and radiopaque.[6] Direct application of a composite material for the definitive core shape is the most common technique.[3,7]

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Similarly, glass fiber reinforced composite (GFRC) posts contain unidirectional glass fibers embedded in a matrix based on resin that is widely used in tooth-colored post systems in practice. One of the advantages of these posts is that they are strengthened without compromising the modulus of elasticity.[8] Furthermore, glass fibers distribute stresses over a broad surface area, increasing the load threshold at which the dowel begins to show evidence of microfractures.[9]

Clinical longevity of post and core restorations is related to the magnitude and direction of the occlusal load, the thickness of the remaining dentin, the design of the post and the quality of cement layer.[10] Thermal loads also have to be taken into consideration because anterior teeth are subjected to different temperatures of ingested food and drinks. Several studies[11-13] exhibit that failure of the post and core system usually occurs cohesively within the cement layer or at interface with dentin. The importance of the micromovement of a cemented post results in the disintegration of the cement and the concentration of stress on the post itself over time.[14] Inasmuch as restorative materials and tooth structures exhibit high different thermal conductivity and coefficients of thermal expansion, thermal loads may even create induced stresses. These stresses might cause fracture of the dental structure, disintegration of the post and core system, leakage of the restoration and finally lead to post and core failure.[15] Although internal stresses caused by thermal loads are clinically important, the investigations of thermal stress distribution on post restored tooth are limited. Furthermore, there is no comparative thermal stress analysis on the tooth-colored, metal-free post and core systems.

The aims of this study were to analyze : (a) the influence of cold heat flow in all ceramic crown material, composite core, zirconium and glass fiber reinforced composite post materials, resin based luting cement and root dentin and (b) to compare these two tooth-colored post systems about their temperature and thermal stress distributions.

MATERIALS AND METHODS

A 3-dimesional finite element model was constructed according to the geometry of maxillary left canine tooth taken from Wheeler's Atlas,[16] post and core, all ceramic crown and supporting dental structures. The crown of the tooth was 11.5 and root was 15.5 mm in length. The all ceramic crown was 2 mm in length at the incisal edge, 1.5 mm at the gingival region with shoulder margin. To obtain the ferrule, coronal dentin with 1.5 mm in height and 1.5 mm in width surviving dentin walls above the cervical curvature of the tooth was formed. Core was modeled with no undercut and 6° convergence angle to simulate the clinical tooth preparation. Post model was modeled as cylindrical shape (15 mm in length and 1.4 mm in diameter) with cone-shaped tip. The tip diameter of the post was 0.8 mm. Luting agent thickness was kept constant at 75 µm around the core and under the cervical curvature of the post materials. To simulate the root filling material, a 6 mm-long conical shape was designed. Cortical and cancellous bone layers were also modeled. Cortical bone was 2 mm in length at the coronal region of the root, 2 mm in width around the root constantly and 3 mm in length at the apical region of the tooth. Cortical bone was surrounded with cancellous bone around the root.

Finite element stress analysis method was used to determine the thermal stress distributions of the tested materials in the current study. This method uses a complex system of points called nodes which make a grid called a mesh. This mesh is programmed to contain the material and structural properties which define how the structure will react to certain loading conditions. Moreover, it solves governing diferential equations by breaking the problem into small elements. In this study, the test model contained 67541 tetrahedral elements and 12308 nodes. 3536 triangular shaped elements were used to mesh the cement layer and root filling material (Figure 1).

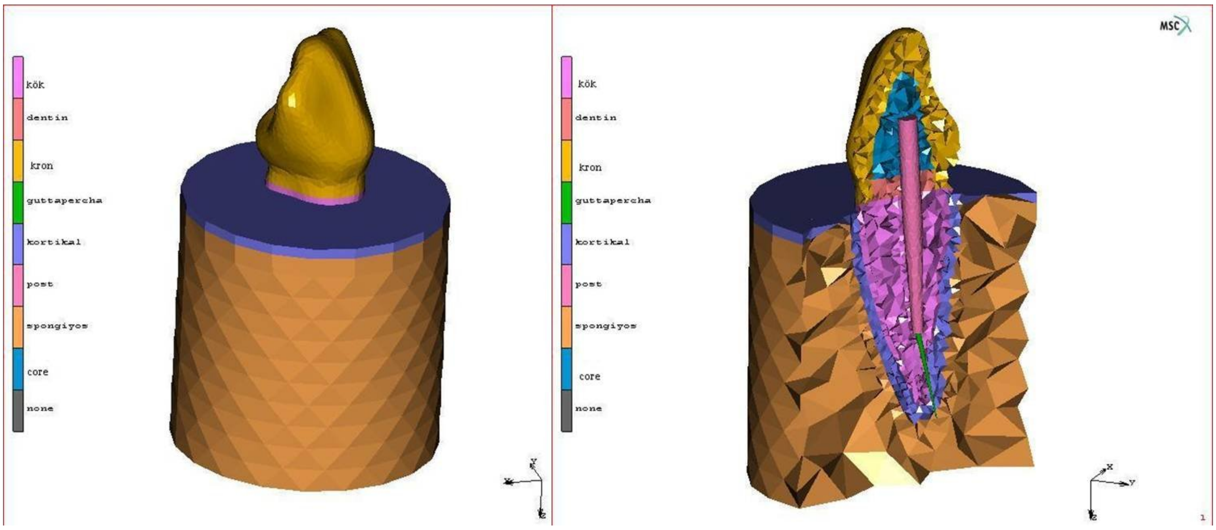

Figure 1. Finite element model contained all ceramic crown, cement layer, core, coronal dentin, post, root filling material, cortical and cancellous bone.

The interface between the cement layer and the other structures was modeled with no gap or slip in cement layer. MENTAT software & MARC Analysis solver (MARC Analysis Research Co, California, USA) were used to generate the mesh, calculate the thermal stress distribution and determine the heat flow between the restorative materials and supportive tooth structures.

All the properties, except the glass fiber reinforced composite resin post, were assumed to be linear and isotropic for all the restorative materials and supportive dental structures.

Thermo-mechanical properties of the materials used for the finite element analysis were determined according to a literature survey[15,17-20] and listed in Table 1 and Table 2.

In the first part of this study, initial body temperature was assumed as 36.5°C and the outer temperature was reduced to 0°C for 5 secs. The analysis was repeated for 5-second-time intervals. In the second part, the thermal stress resulting from temperature change was calculated.

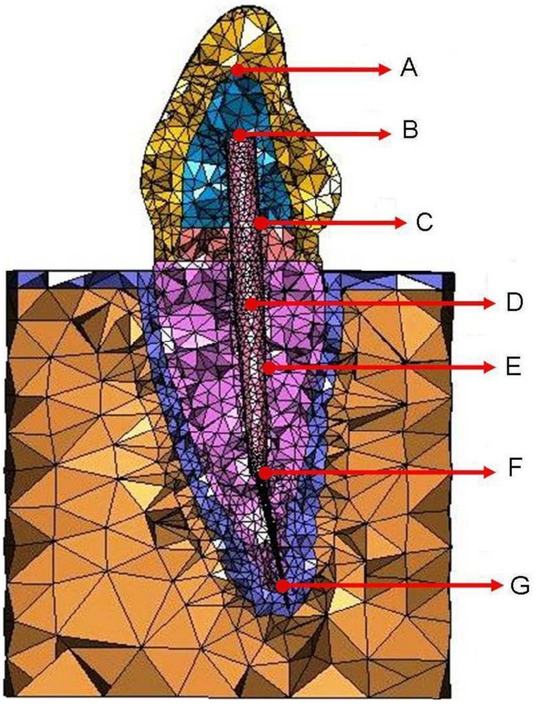

Figure 2. The nodes used in the study. A: All ceramic restoration and core junction, B: Post and core junction, C: Post, ferrule and core junction, D: The middle of the post, E: Post and adhesive cement junction, F: Apical edge of the post, G: Apex of the root.

For the analysis, 7 nodes (Figure 2) of the finite element model were selected and the evaluation of heat flow, temperature and thermal stress distribution on the dental restorative materials and the tooth structures was done by the aid of these nodes, then the data were compared. Maximum thermal stress and temperature values were determined on some critical surfaces (e.g. crown and core junction area, composite core, post materials and root surface), as well.

Table 1. Thermal and mechanical properties of the materials used in the analysis.

Material	**Young's Modulus (MPa)**	**Possion's Ratio**	**Density (kg/m^3)**	**Thermal Expansion Coefficient (1/°C)**	**Spesific Heat (J/kg/K)**	**Thermal Conductivity (W/m/K)**
Dentin	14715	0.31	2100	$8.3 . 10^{-6}$	280	627.6
Cortical Bone	14715	0.30	1300	$10 . 10^{-6}$	440	586.8
Cancellous Bone	490.5	0.30	1300	$10 . 10^{-6}$	440	586.8
All Ceramic	70000	0.25	2400	$17 . 10^{-6}$	980	1467
Composite Resin	14519	0.24	2100	$39.4 . 10^{-6}$	200	1087.8
Resin Cement	8300	0.24	2240	$30 . 10^{-6}$	830	1094
Gutta Percha	0.69	0.45	2700	$162 . 10^{-6}$	1042	332.4
Zirconia Post	210000	0.23	6080	$10 . 10^{-6}$	450	2800
Glass Fiber Reinforced Composite Resin Post	**Orthotropic**	**Orthotropic**	2100	6×10^{-6} **in length** 50×10^{-6} **across**	580	1350

Table 2. Young's Modulus and Possion's Ratio of the glass fiber reinforced composite resin post according to the manufacturer.

Young's Modulus(GPa)		**Poisson's Ratio**	
E_L	45000	$\nu_{LT}=\nu_{LT^1}$	**0,24**
$E_T=E_{T^1}$	12000	$\nu_{TL}=\nu_{T^1L}$	**0,07**
$G_{LT}=G_{LT^1}$	3600	ν_{TT^1}	**0,30**
G_{TT^1}	**4600**		

RESULTS

Temperature and von Mises stress distribution of the measurement points after 0°C cold irritant application was given in Table 3. Mean temperature value was 15.75 °C for GFRC post model and 15.47 °C for Zr post model.

Table 3. Temperature and thermal stress distribution of selected nodes in both post models.

	GFRC Post								**Zirconia Post**							
Nodes	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**Mean**	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**Mean**
Temperature (°C)	0.00	0.05	0.74	11.08	27.74	34.50	36.10	15.75	0.01	0.19	1.05	11.25	26.02	33.74	36.05	**15.47**
von Mises Stress (MPa)	12.7	10.5	16.5	9.12	3.54	0.47	0.02	7.55	12.7	11.5	16.9	2.97	1.94	0.36	0.017	**6.63**

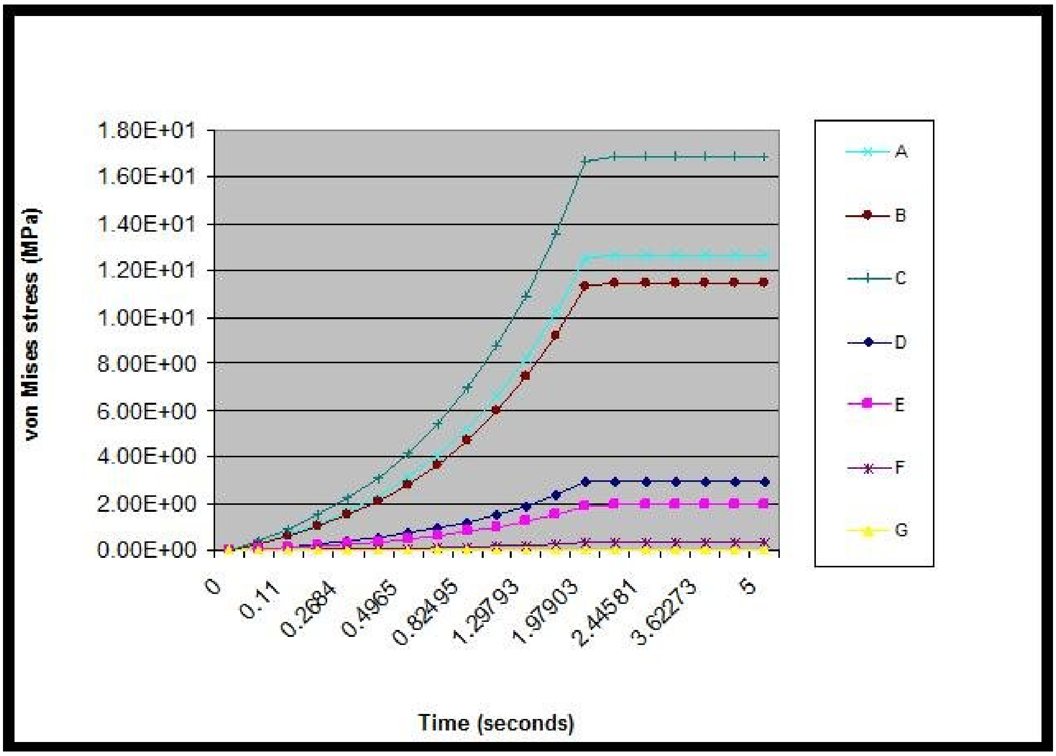

Figure 3. Thermal stress change of tested nodes in zirconia post model.

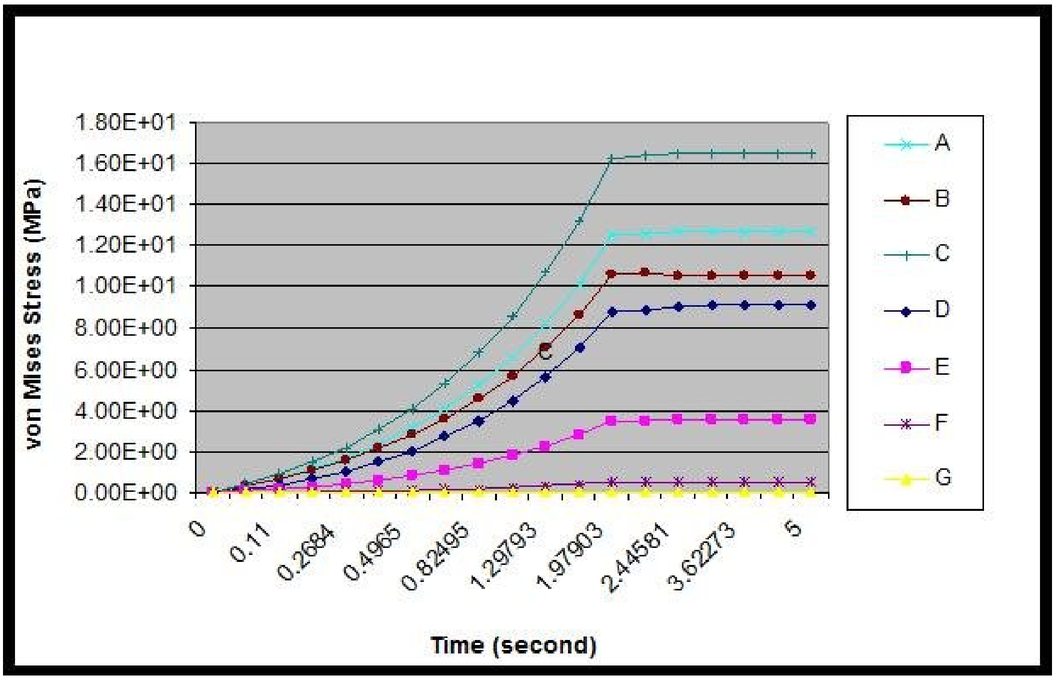

Figure 4. Thermal stress change of tested nodes in GFRC post model.

It was found out that temperature values at A, B C and D points decreased suddenly in 1.5 s and then rose to the mouth temperature in 5 s. Temperature changes were nearly the same at nodes A and B. As shown in Figure 3, cold liquid caused von Mises stress in all points. The maximum von Mises stress was observed at the node C in both post systems. Minimum temperature changes took place at the nodes F and G. In general, thermal stress was observed in the cervical part of all-ceramic crown and the interface between root dentin-composite core and post material. On the contrary, they decreased from the cervical part to the apical edge of the post materials. The stresses occurred on the most apical edge of the post materials (node F) and the apical region of the tooth (node G) was considered negligible when compared to the normal oral cavity temperature. The thermal stress change of tested nodes in both post systems were given in Figures 3 and 4. The temperature gradient of the GFRC post was smaller than that of the zirconia post. Maximum Equivalent von Mises stress occurred in the junction of the middle third of the posts and resin cement. These thermal stress values were 33.7 MPa for glass fiber reinforced composite post and 40.1 MPa for zirconia post. Moreover, on the junction of composite core and post materials, these values were 20.3 MPa for glass fiber reinforced composite post and 22.7 MPa for zirconia post. Additionally, Maximum Equivalent von Mises stress values on the root dentin were 13.3 MPa for glass fiber reinforced composite post and 12.7 MPa for zirconia post. Maximum Equivalent von Mises stress distribution on the models was shown in Figure 5a-f.

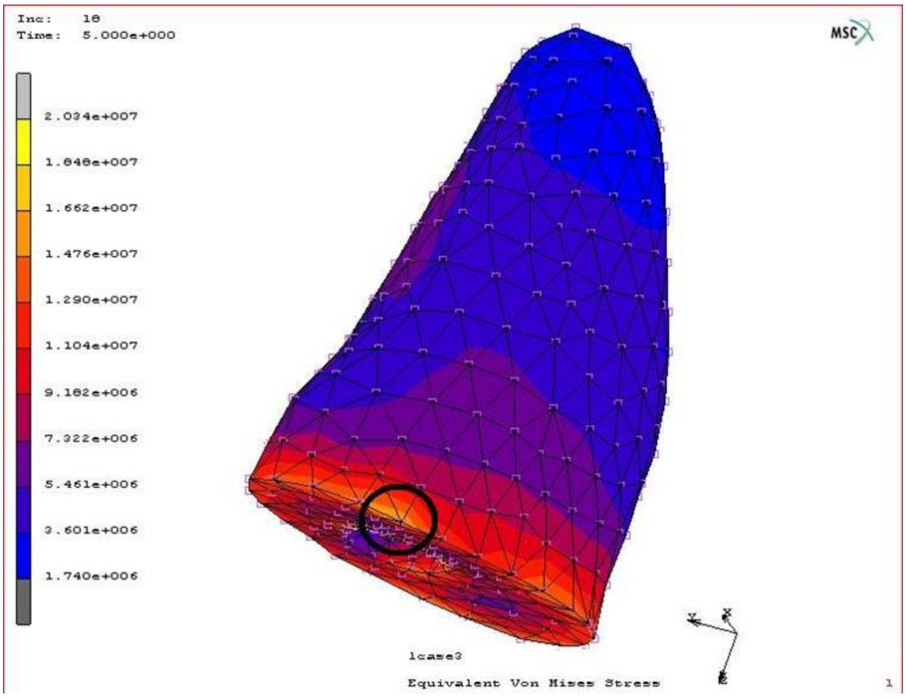

Figure 5a. Maximum equivalent von Mises stress at composite core in GFRC post model.

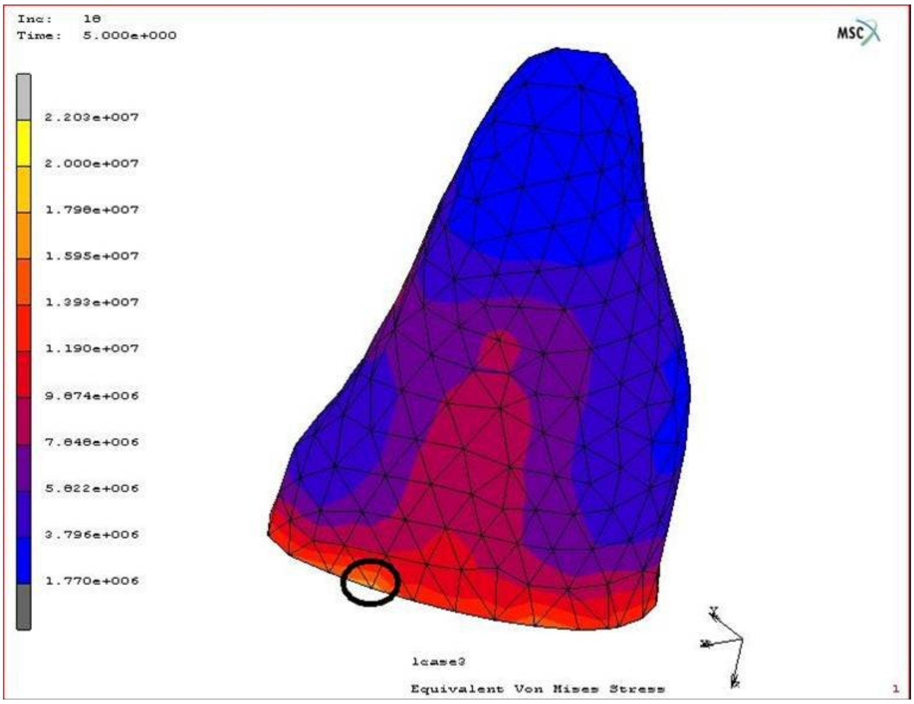

Figure 5b. Maximum equivalent von Mises stress at post surface in zirconia post model.

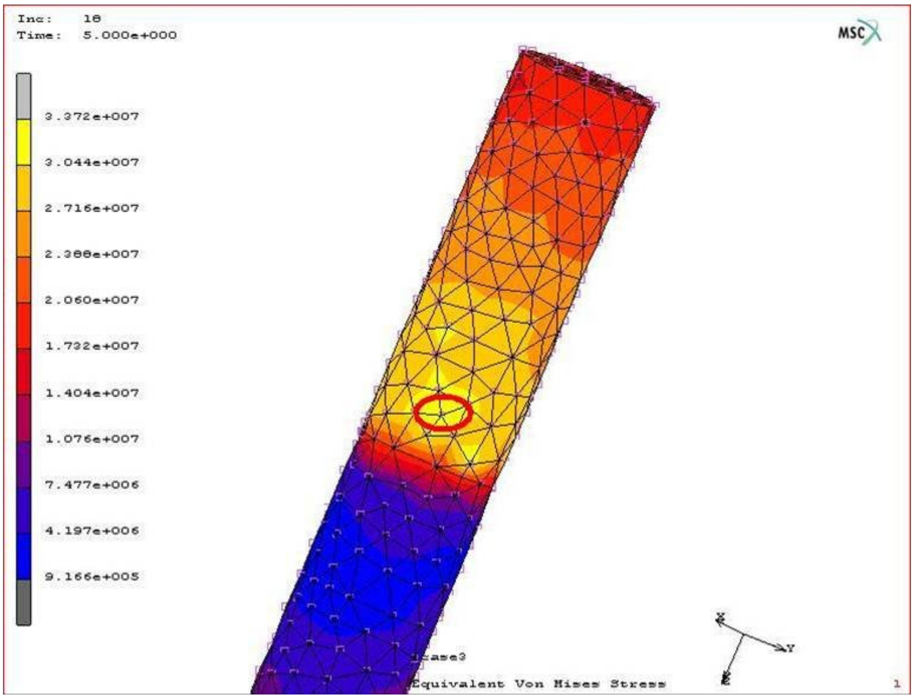

Figure 5c. Maximum equivalent von Mises stress at post surface in GFRC post model.

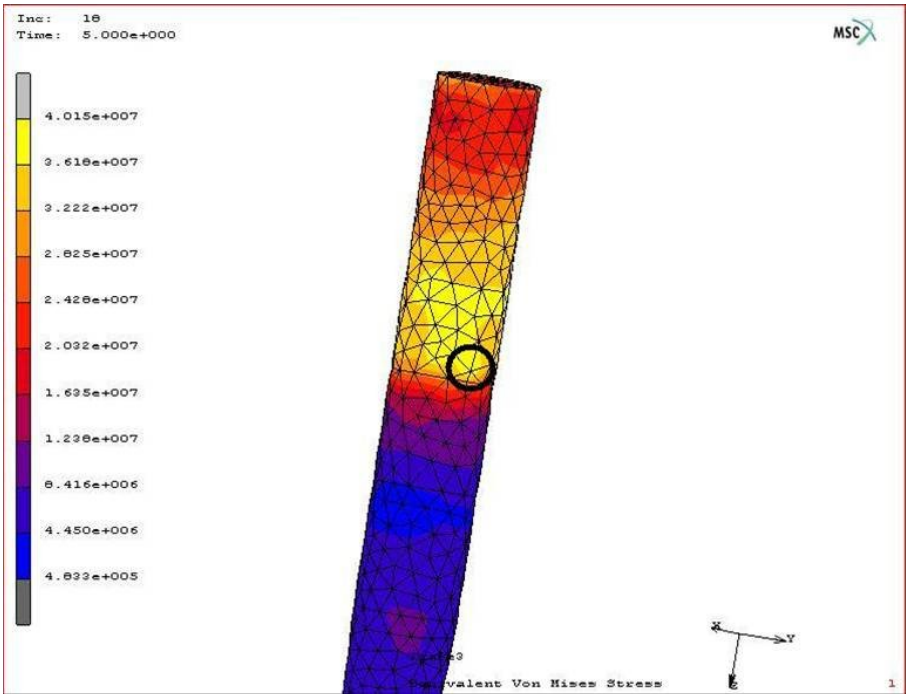

Figure 5d. Maximum equivalent von Mises stress at post surface in zirconia post model.

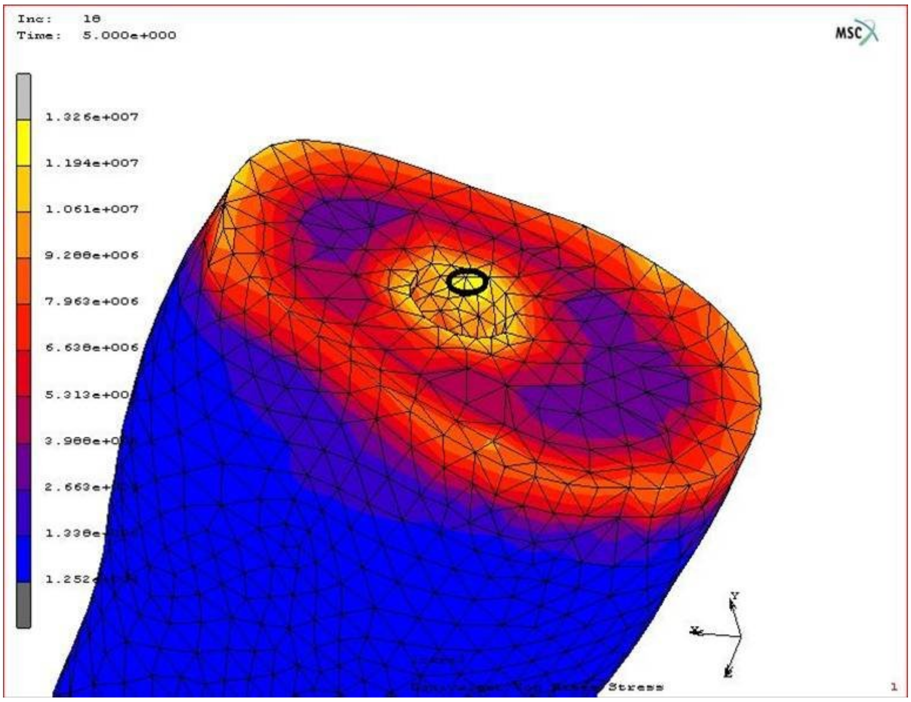

Figure 5e. Maximum equivalent von Mises stress at root dentin in GFRC post model.

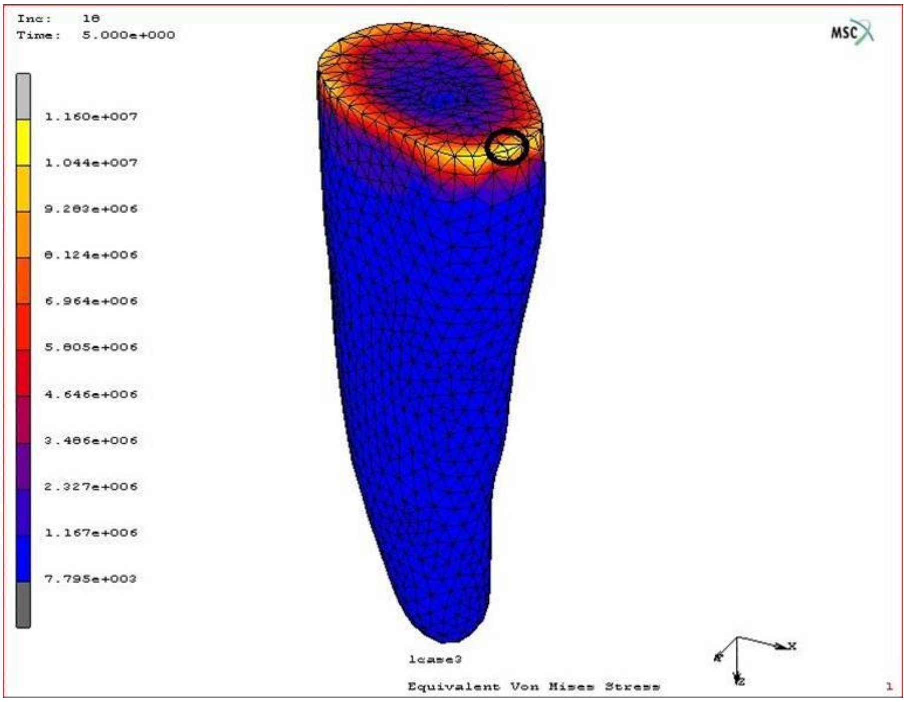

Figure 5f. Maximum equivalent von Mises stress at root dentin in zirconia post model.

DISCUSSION

Thermal diffusivity is an important parameter in transient heat transport problems.[21] Hot and cold liquid drinks in the mouth cause a temperature gradient that result in thermal stresses because of different physical and thermal properties of different materials in the restored tooth. The thermal stresses which occur in the restored tooth depend on many factors such as the properties of restorative materials, preparation design and adhesive resistance between tooth and restorative materials.[22] Finite element stress analysis (FEM) method allows the examination of the temperature flow and thermal stress that is produced by thermal expansions and contractions in the complex dental systems at the interfaces between different biomaterials.[23,24] In the current study, a 3-dimensional FEM has been arranged to calculate node temperatures and the thermal stress distribution in a restored tooth. Yang et al.[15] constructed a 2-dimensional finite element model and investigated the thermal stress distribution on 3 different metals and a carbon fiber reinforced composite post systems with various core restoratives. Toparli and Sasaki[25] also investigated the thermal change and thermal stresses on metal alloy post systems, using an axisymmetric finite element model. Besides these studies, a 3-dimensional finite element model was constructed using a 3D model to simulate the actual situation more closely to avoid inaccuracies seen in 2D model results,

To analyze the stress distribution in the analysis, all materials, except GFRC post, were assumed to be linearly elastic and isotropic and they remained elastic under applied thermal loads. The cement was assumed to bond perfectly to restorative materials.[26] Metal and zirconia posts had a homogenous (isotropic) structure whereas fiber reinforced composite posts were anisotropic.[27] Due to the anisotropic nature of fiber reinforced composite, besides the mechanical properties, the fiber orientation also influenced the thermal behavior of the material.[27] In the lights of this information, the anisotropic properties of GFRC post were used in this study.

Thermal loads were also considered because the teeth are subjected to different temperatures of ingested food and drinks. Palmer et al.[28] recorded of the variations of temperature during the imbibing of hot and cold foods and beverages in the oral environment and determined the data range between 0°C and 67°C. In accordance with this finding, 0°C cold heat application was selected in this investigation.

In this investigation, different tooth colored post-and-core materials with a low thermal conductivity increased the thermal gradient in restorative materials and tooth structures (Figure 4). The temperature gradient of the GFRC post was smaller than that of the zirconia post because of differences in thermal conductivity. Temperature changes in the cement layer of the models (GFRC post model and zirconia post model) were much greater at the coronal section of the core than at the middle or apical sections of the posts (Table 1). However, von Mises stresses were much greater at the junction of post materials than at the coronal section of the core and the junction between core and resin cement. Moreover, the temperature change had more remarkable effect on the cervical area than on the other areas. Additionally, thermal stress from the thermal gradient in the zirconia post generated an additional stress in the cement layer. This would support the finding that failures of these systems occured cohesively within the cement or at its interface with dentin[29] rather than in the dentin. The peak dentinal stress of the GFRC post was slightly lower. In this study, thermal analysis showed that stress level was closely related to the degree of thermal gradient. The thermal stress of zirconia post was greater than that of GFRC post.

The *in vitro* evaluation of temperature changes is conventionally performed and widely accepted by researchers, considering that in some cases it is not possible to use vital teeth for ethical reasons. However, it must be pointed out that the experimental methods are sometimes unable to reproduce the *in vivo* conditions, such as the influence of the oral environment, the presence of saliva, body temperature, blood flow, vital tooth conditions, and others. In this investigation, the decrease of temperature has increased the von Mises stresses remarkably. Relative mechanical performances of the post systems under both the temperature load and the occlusal force are very different from those under occlusal force only.[15] However, it has been considered in this study that temperature changes caused by cold beverages may increase the potential of post failure.

CONCLUSIONS

On the basis of the thermal stress analysis, it can be concluded that zirconia posts produce greater stress than GFRC posts. Temperature changes have more effect on the post-cement interface and cervical areas than on the other areas.

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