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Comparative Evaluation of Stress Distribution on an endodontically treated deciduous maxillary central incisor restored with different post materials under various traumatic loading conditions: 3-D Finite Element Analysis

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Abstract

Introduction: Determination of stress distribution in post-core restored endodontically treated teeth is challenging due to the fact that the post and core system, the root and its canal, and the bony structures supporting the root have small dimensions and are structurally complex. Due to this, most biomechanical research has been performed in-vitro and in-vivo, but was unsuccessful to explain the internal behavior of the structures. Finite Element Analysis (FEA) makes it possible to evaluate the stresses and strains in the living structures under various external forces.

Aim: To evaluate and compare the influence of stress distribution in deciduous maxillary central incisors restored with various post and core combinations.

Materials and Methods: A 3D finite element model of an endodontically treated deciduous maxillary central incisor tooth was generated and geometric models were developed using pro/engineer which were meshed into elements. Vertical, horizontal, and oblique loads of 150 N were applied on the crown to simulate horizontal traumatic impact, ideal primary occlusion and vertical traumatic impact respectively. Von-mises stresses in dentin, posts, cores and crowns were determined using ANSYS Software

Results: Horizontal loading condition was found to be the most dangerous, which caused highest stresses in dentin and posts, followed by oblique loading and vertical loading conditions. It had been found that the stress distributions in root dentin were most uniform when the Modulus of elasticity of the posts and cores were similar to that of the dentin.

Conclusion: The post with higher elastic modulus caused higher stress concentrations and less uniform stress was distributed in both dentin and the posts with vertical loading. Horizontal loading was more supported by Zirconia post (highest elastic modulus post) thus minimum stress value to the root-dentin were noticed. Oblique loading was well supported by Glass-fiber post, Ribbond post, and even Dentin post. Vertical loading was more supported by Glass-fiber post.

Keywords: Finite Element Analysis, Stress distribution, Glass-fiber post, Zirconia post, Ribbond post, Dentin post

Introduction

Early childhood caries (ECC) is a devastating condition for both the child undergoing the dental treatment and the concerned parent.[1] It is characterized by affecting the maxillary anterior teeth followed by molars. The early loss of primary teeth results in problems such as decreased masticatory efficacy, decrease in vertical dimension, development of Para-functional habits, speech, esthetic-functional problems like malocclusion and space loss, and psychological problems that may intervene in personality and behavioral development of child.[2]

Restorations of decayed primary maxillary anterior teeth mainly at the cervical third of the crown are usually a clinical dilemma for every Pediatric dentist.[3] As a consequence of the extensive carious decay with pulpal involvement and endodontic intervention, there is severe loss of the coronal structure.[1] Several attempts have been made by clinicians to restore grossly decayed anterior primary teeth with strip crowns, polycarbonate crowns, veneered stainless steel crowns, and art glass crowns.[4] But these restorations have failed to withstand the occlusal and external forces. Hence, the innovative intra-canal posts and core systems such as modified Omega shaped orthodontic wires,[3,5] biological posts,[6,7] fiber core posts, Polyethylene Fiber Reinforced Posts (PFR)[8] and glass reinforced fiber composites have been introduced to overcome the problem of fracture of restoration of such teeth with extensive loss of tooth structure.[2,9]

In recent years, stress analysis has been a topic of interest in determining stresses in the dental structures and improvement of the mechanical strength of these structures.[10] Being a complex biomechanical system oral cavity has limited access. Due to this, most biomechanical research has been performed in-vitro and in-vivo studies, but was unsuccessful to explain the internal behavior of the structures.[11] Finite Element Analysis (FEA) makes it possible to evaluate the stresses and strains in the living structures under various external forces.[10]

Finite Element Analysis (FEA) is a modern, powerful and a valuable analytical tool for complex biomechanical analysis in biological research.[11] The finite element method (FEM) involves a series of mathematical computational procedures to calculate the load distribution in each element. The results obtained can then be studied using visualization software to view a variety of parameters, and to fully identify implications of the analysis.[12] FEA has various advantages compared with studies on real models like understanding the biomechanics of fracture under simulated traumatic loads.[11] The idea of FEA is to obtain a solution of a complex physical problem by dividing the problem domain into a set of much smaller and simpler domains. In these domains, the field variables can be interpolated with the use of shape functions. The structure is further discretized into "elements" connected through "nodes". Choosing the appropriate mathematical model, element type and degree of discretization are important factors in FEM to obtain accurate results as well as time and cost effective solutions. FEA is capable of computationally simulating the stress distribution and predicting the sites of stress concentrations, which are the most likely points of failure initiation within a structure or material.[13]

The selection of a post system in deciduous teeth is still controversial because of the variability of materials currently available to improve the mechanical behavior of the weakened tooth to that of intact tooth.[3] Some researchers recommended posts with high modulus of elasticity, while others advocated that posts with modulus of elasticity close to that of dentin served better in stress distribution pattern. Therefore, Dentin post as the recent advancement in the field of dentistry is being introduced in the study with various combinations and varying loading condition.

The purpose of this study was to analyze the stress distribution in endodontically treated deciduous maxillary central incisor restored with different post materials when subjected to different directional loads by using a finite element method.

Aim: To evaluate and compare the influence of Stress Distribution in Deciduous Maxillary Central Incisors restored with different post materials.

Objectives: The objective was to attain an extensive knowledge of the mechanical performance of the post-core restored endodontically treated teeth and to evaluate the stress distributions in a post-core restored endodontically treated deciduous maxillary incisor.

Materials & Methods

General Steps of Finite Element Analysis (FEA):

Construction of the Geometric model:

A freshly extracted, sound Deciduous Maxillary Central Incisor with fully formed root and absence of cracks, fractures, and caries was used to prepare a 3-D Finite element model **(Fig.1)** of the tooth. Images of the tooth with 0.5 mm cross-sections were acquired using a spiral CT scanner. The enamel, dentin, and pulp boundaries were determined based on the CT images, and a 3-D digital model was thus prepared using Pro/Engineer software ANSYS. Considering this FE-Model as a standard geometric model, other experimental models were generated.

- **Conversion of geometric model into finite element Mesh**

Once the geometric model was generated, the models were imported into ANSYS software to create the Finite Element Mesh-Model. The mesh generation was done to sub-divide the solid geometry into elements to create a Mesh-model. ANSYS 15.0 Software was used to create the mesh-model of endodontically treated post restored maxillary deciduous central incisor. The model had 24312 elements and 45803 Nodes after Meshing. In FEA, each element was assigned a pre-determined number of nodes. The elements were connected to one another with the help of their nodes. The Meshed model is shown in (**Fig.2**).

Assembly/ Material property data representation:

Restorative materials used in the study were selected because of their different elastic moduli. The details of the material property like Young's Modulus of Elasticity and Poisson's Ratio values of the tooth and supporting tissues were taken from other research references and is mentioned in the tables (Table: 1, 2 & 3). Following which, values were introduced into the program. The distributions of stress in different restorative materials were investigated using FEA with a software program, ANSYS 15.0 (Swanson Ansys Inc., Houston, PA, USA).

Four Different Posts Materials used in study:

1. Glass-fiber Post
2. Zirconia Post
3. Ribbond Post
4. Dentin Post

Preparation of the virtual tooth obturation:

Obturation of the canal was simulated with the obturating material i.e. Zinc-oxide eugenol cement in the apical part of the root canal space followed by Glass- ionomer cement apical to the post-space. Rest of the space was utilized as the post-space.

Preparation of the virtual post-space

Of the total canal length, 6 mm of space was occupied by the zinc oxide eugenol and 1mm of space by glass ionomer cement apical to post space. Rest of the 3 mm of space was considered to be the virtual post-space which was occupied by the intra-canal post and 4 mm of post was used in core-build up.

Sstandardization of Post

In terms of the comparison of the structural evaluations, the following arbitrary commercially available post geometry was chosen. The glass fiber composite post used was opaque, smooth, round and non-serrated 1.35 mm in diameter and 7 mm in length. The measurement taken for the intra-canal post was 3 mm and 4 mm of extra-canal post and core **(Fig. 3).** Crown anatomy simulated similar to the dimension of the solid model used as control model. Composite resin was used for cementation of post and core-build up. Similarly, 3-D models of the supporting tissues of the tooth were prepared using Pro/Engineer software.

Loading configuration

The generated model was subjected to point load of 150 N in three different directions (Horizontal, Vertical, and Oblique) to simulate the three different forces. The Maximum Von-Mises stresses were analyzed on the root-dentin, assuming that the fracture of a brittle root is mainly associated with Von-Mises stresses. The stress analysis was carried out using ANSYS Software. **(Fig. 4)**

Horizontal Load : was applied on the labial surface of the crown to simulate horizontal traumatic impact on the endodontically restored incisor tooth with different post & core combinations,

Vertical Load was applied at the center of the incisal edge of the crown to simulate the vertical traumatic impact on the endodontically restored incisor tooth with different post & core combinations, and

Oblique Load was applied at 148^0 to the incisal edge of the palatal surface of the primary anterior to simulate ideal primary occlusion with masticatory impact on the endodontically restored incisor tooth with different post & core combinations.

Processing and post processing /Analysis of Stress Pattern: The analysis of the stress pattern was done to assess the maximum Von-Mises Stresses acting upon the materials and the tooth structures during application of various directional loads. The results were demonstrated using Von-Mises criterion and numerical data was calculated in Megapascals (MPa). The comparisons of stresses were made between different experimental models. The stress values obtained were then transformed into color graphics for better visualization. Evaluation of the results was made based on the colored patterns where warm colors (shades of red) denoted the higher stress values and cold color (shades of blue) depicted the minimum stress values.

Results

The maximum Von-Mises stresses were analyzed and compared in various parts such as crown, core, post and root-dentin of endodontically treated teeth restored with post and core with four different post materials of varying Elastic Modulus and Poisson's Ratio under different directional loads: Horizontal (Refer Table-4 and Graph-1), Oblique (Refer Table-5 and Graph- 2) and Vertical (Refer Table-6 and Graph-3).

In this study we observed that post material influenced the stress distribution in the tooth. Several authors in their studies revealed the effect of post material on stress distribution. Gurbuz et al.[14] stated that a more uniform distribution of stress in the entire post-and-core restoration and within the dentin would be achieved, if the modulus of elasticity of the post material was similar to that of the core material. Afroz A. et al.[15] found that the risk of root fracture increased with the use of a rigid post material due to the generation of high stress concentration. According to the study conducted by Silva et al.[16], the post material was found to be an important factor in contribution to the stress distribution in dentin than the external configuration of the post. Some authors considered the design of the post to be the contributing factor in stress distribution.[17,18,19,20,21] Other authors like Adanir et al.[22], in their investigation evaluated the effects of different post materials on the stress distribution in maxillary central incisor under different loading conditions. They concluded in their study that Metallic posts had greater stress concentration at the post-dentin interface than fiber posts. They also stated that the physical characteristics of posts were important on stress distributions. In the present research we found that the post with the highest young's modulus of elasticity served better in all the loading conditions as it absorbed maximum stress.

In the current study, the stress distribution observed in crown did not change significantly in horizontal and oblique loading irrespective of post material. However, they changed significantly during vertical loading. Similarly, horizontal loading caused the highest stress in the dentin and post followed by the oblique load and finally the vertical load. In case of core, the stresses were nearly similar in horizontal and oblique loading. However, they significantly changed when vertical loading was applied.

In our study there was uniform stress distribution in the middle third and the apical portion of the root, i.e., no stress concentration was seen around the post, but the cervical stresses were high. This finding corroborates with those reported by Pegoretti et al[23] who suggested that the stresses at the cervical margins could be lowered using less stiff crown materials. Similarly, Alessandro Lanza et al. in their finite element analysis (FEA) observed favorable stress distribution in case of restoration using flexible glass post. They concluded that the ideal root canal post must be sufficiently elastic to accompany natural flexural movements of the structure of tooth, something that a rigid metal post cannot do.

We found that the post with higher elastic modulus caused higher stress concentrations and less uniform stress was distributed in both dentin and the posts with vertical loading. The post with higher elastic modulus bears more loads. With low elastic modulus, the post flexed easily and did not support much of the load. Overall, the horizontal loading and the oblique loading were the most dangerous. The post material along with the loading conditions made significant difference on the magnitude of stress and their distribution in dentin.

Discussion

Intra-canal post and core are the commonly used restorations for endodontically treated teeth when the teeth have excessive coronal damage. Loosening of post and core or fracture of remaining root dentin are most frequent problems observed. The analysis of the stress distribution in post-core restored endodontically treated teeth will contribute to our understanding of the causes of the high incidence of restoration failure in these teeth and may result in the modification in design of post and core restorations for improved clinical performance.

The design of the post and the nature of material of post and core are very important in dentinal stress distribution.[24,25,15,26] The mechanical properties, such as elasticity and stability of the materials, used in the preparation of the core structure are of great importance as the core structure transfers the load from the crown to the post. Shalini et al.[27] and Verissimo et al.[28] stated that the purpose of using products that had mechanical properties closer to dentin and enamel was to obtain best retention and resistance of the restoration from dislodging or occluding forces, hence protecting the remaining tooth structure. Therefore, a biological post was used in the current study, i.e. Dentin Post (whose elastic modulus is similar to dentin).[4]

For the assessment of stress measurement and evaluation, numerous techniques have been applied, including the strain gauge method,[29,4,30,31] the loading test,[32] and the photo elastic method.[27,25,33] These techniques being homologous and two dimensional, were tough to reproduce at times. An acceptable index of stress distribution at the root structure becomes difficult to create based mostly on experimental and clinical observation.[4] To deal with unrealistic engineering problems, an innovative theoretic method named Finite element analysis (FEA) is being used.

The FEM is powerful and versatile method extensively been used in dental biomechanics research for investigating complex systems that are difficult to standardize in-vitro and in-vivo studies. It can provide detailed information on stresses, strains and displacements within complex structures such as teeth and restored teeth with post-core materials.

A 3-D finite element model was developed to evaluate the stress distribution in an endodontically treated deciduous maxillary incisor restored with different post-core combinations under various static loads. Different post-materials were investigated on the stress distributions in various parts of a post-core restored maxillary incisor. Von-Mises stress criterion for evaluating the stress distribution was used**.** A qualitative analysis of the stress distribution was done in the post, core, and root-dentin. The stress distributions are shown in cross-sections passing through the tooth longitudinal axis and loading directions since such a cross section shows the highest stresses for horizontal and oblique loading. Stress values obtained in numerical data were transformed into color graphics.[34,4,35,36] Li et al.[37] explained the interpretation of color template which was representative of stress values. Warm colors (primarily red, orange, and yellow) [36,38,35] were suggestive of tensile stresses, while cold colors (primarily shades of blue)[39,24] denotes areas of compressive forces following load application.

3-D models of the tooth were subjected to three different type of loadings; Horizontal, Oblique, and Vertical and all with a magnitude of 150 N. The loading force was taken within the maximum range of bite force in children of 3 to 5.5 years old. Rentes et al.[40] suggested the maximum bite force in primary dentition with normal occlusion to be 213.17±43.97 N. The direction of forces can vary from horizontal, vertical, or oblique depending upon conditions like biting force, masticatory forces, bruxism and trauma etc. In horizontal load, the direction of force applied was perpendicular to the long axis of tooth simulating horizontal traumatic forces.[41,42,19] In vertical load, direction was parallel to long axis of tooth simulating vertical traumatic impact.[41,19] In oblique loading, load was applied at 148^0 to incisal edge of palatal surface of primary anterior to mimic the ideal occlusion of the primary anterior teeth.[9,27,19,43,44] Gurbuz et al.[14] also did a study with similar force application on posts in primary teeth.

Conclusions

Based on the findings of the above study, the following conclusions have been drawn:

Four different posts (Zirconia post, Glass-fiber post, Ribbond Post and Dentin post) were taken with varying elastic modulus and Poisson's Ratio to evaluate the stress distribution in crown, dentin, post, and core under different directional loads.

- **Crown:** During vertical loading, the stresses observed in the crown was maximum in comparison to horizontal and oblique loading regardless of the post material used. Horizontal loading showed a more uniform stress distribution in crown with all the four posts. The Glass-fiber post and Ribbond post exhibited lowest stress in crown under oblique loading condition.
- **Root-dentin:** Stresses observed in the root-dentin were greatest with horizontal loading followed by oblique and vertical loading regardless of the post material. The post with highest Young's modulus (Zirconia Post) showed a less stress in root-dentin as the post itself absorbed maximum amount of forces. High stresses are highly undesirable because they may cause the fracture of dentin and failure of the restored tooth.
- **Post:** The stress distribution noticed in post was greatest with high young modulus of elasticity post (Zirconia Post) irrespective of different directional loading condition. The horizontal loading is the most dangerous, followed by the oblique load while the vertical load gives the lowest stress. Different post materials made significant differences in the magnitude of stresses and their distributions.
- **Core:** The stresses transmitted to the core were greatest during horizontal and oblique loading condition and vertical load showed the lowest values irrespective of the post material used. This concludes that greatest impact on the core is during horizontal and oblique loading conditions which can leads to fracture of the core of the restoration.

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Legends Figure

Fig. 1 Solid model of intact tooth (3D View)

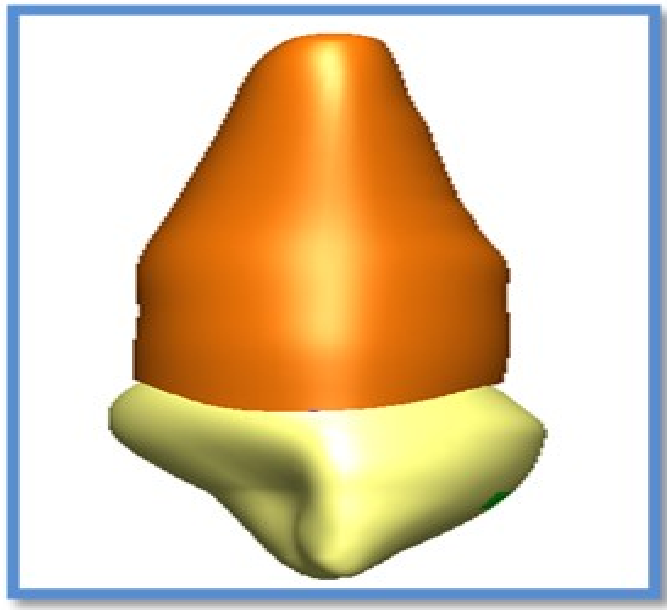


Fig. 2 Meshed model (3D View)

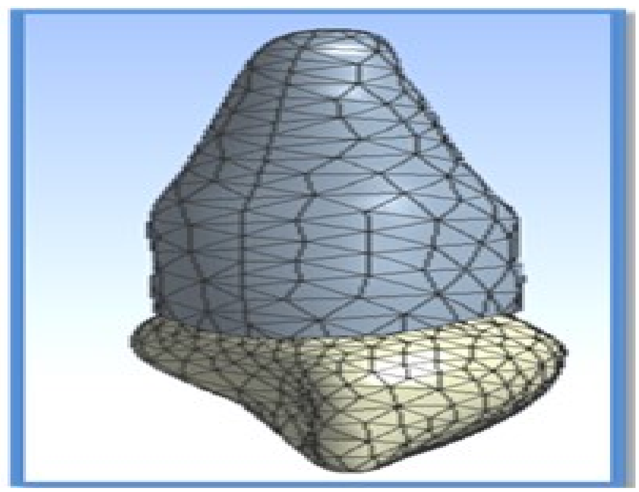


Fig.3 Standardization of post

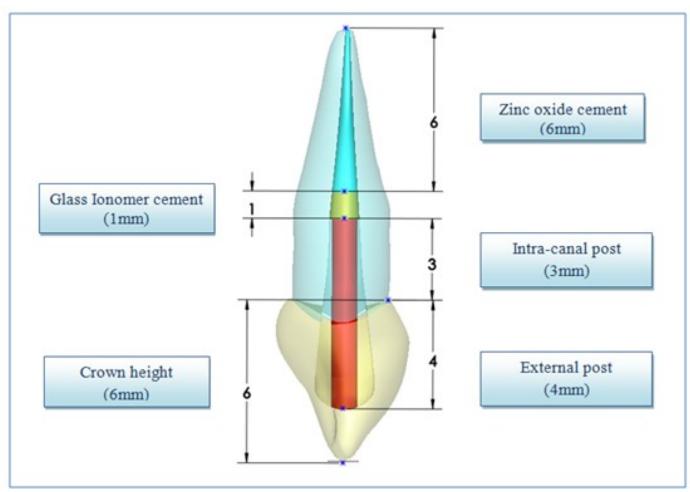


Fig. 4 Loading Configurations

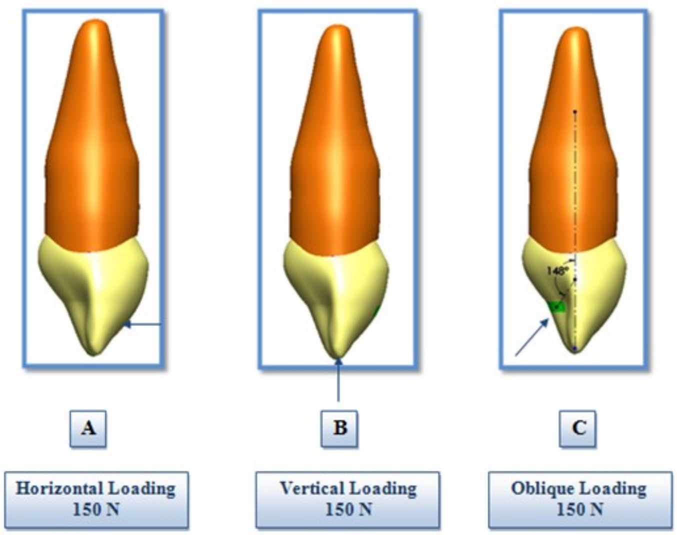


Table: 1 ***Mechanical Properties of Tooth***

Material	Young's Modulus of elasticity (MPa)	Poisson's Ratio	Reference
Enamel	80350	0.33	Gurbuz et al[14]
Dentin	19890	0.31	Gurbuz et al[14]
Pulp	2	0.45	Gurbuz et al[14]
Cortical Bone	14700	0.30	Gurbuz et al[14]
Spongiose bone	490	0.30	Gurbuz et al[14]
Periodontal ligament	69	0.45	Gurbuz et al[14]
Cementum	18600	0.3	Desai et al[10]
Gingiva	0.019	0.3	Adanir et al[22]

Table: 2 ***Mechanical Properties of Restorative Materials***

Material	Young's Modulus of elasticity (MPa)	Poisson's Ratio	Reference
Glass ionomer cement	10800	0.30	Gurbuz et al[14]
Zinc Oxide Eugenol	288	0.40	Farah et al[17]
Zirconia Crown	205000	0.26	Prabhakar et al[45]

Table: 3 ***Mechanical Properties of Posts***

Material	Young's Modulus of elasticity (MPa)	Poisson's Ratio	Reference
Glass-fiber Post (G.P)	45000	0.24	Adanir et al[22]
Zirconia Post (Z.P)	210000	0.23	Adanir et al[22]
Ribbond fiber + bonding agent + Tetric flow (R.P)	23600	0.32	Gurbuz et al[14]
Dentin Post	18600	0.31	Memon et al[4]

Table 4: Maximum Von- Mises Stress values in various part of tooth restored with different post materials under **Horizontal** load

Von-Mises Stress (MPa)*	Glass-Fiber Post	Zirconia Post	Ribbond Post	Dentin Post
Crown	64.96	64.96	64.93	64.91
Root-dentin	31.74	28.25	31.74	31.74
Post	28.79	90.71	15.87	13.68
Core	28.10	28.91	27.36	27.47

Table 5: Maximum Von- Mises Stress values in various part of tooth restored with different post materials under **Oblique** load

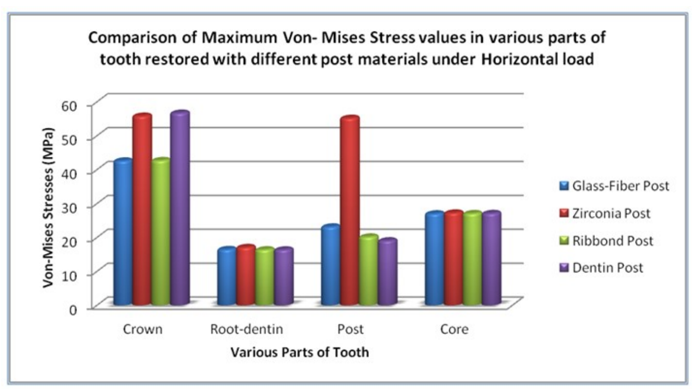
Von-Mises Stress (MPa)*	Glass-Fiber Post	Zirconia Post	Ribbond Post	Dentin Post
Crown	42.61	55.82	42.72	56.71
Root-dentin	16.48	17.10	16.40	16.39
Post	23.16	55.20	20.18	19.07
Core	27.01	27.27	27.08	27.12

Table 6: Maximum Von- Mises Stress values in various part of tooth restored with different post materials under **Vertical** load

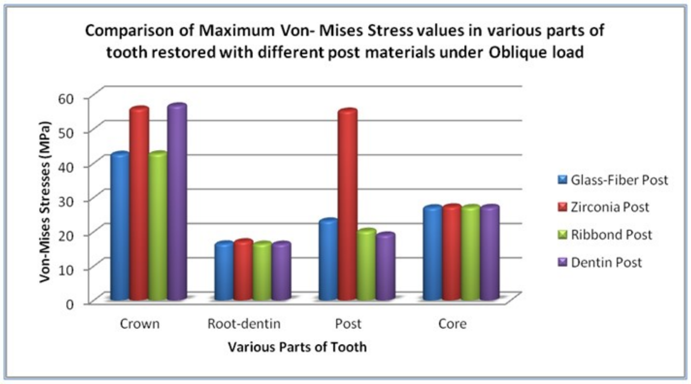
Von-Mises Stress (MPa)*	Glass-Fiber Post	Zirconia Post	Ribbond Post	Dentin Post
Crown	87.81	88.40	87.69	87.65
Root-dentin	9.37	11.32	9.72	9.83
Post	13.94	48.94	7.33	6.00
Core	6.44	6.44	6.31	6.34

*Mega Pascal: (1 MPa = 1,000,000 Pascal)

Graph 1: Comparison of Maximum Von- Mises Stress values in various part of tooth restored with different post materials under **Horizontal** load



Graph 2: Comparison of Maximum Von- Mises Stress values in various part of tooth restored with different post materials under **Oblique** load



Graph 3: Comparison of Maximum Von- Mises Stress values in various part of tooth restored with different post materials under **Vertical** load