Journal of Bioscience and Bioengineering
Vol. 104, No. 5, 363–370. 2007
DOI: 10.1263/jbb.104.363

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Effect of Variation of Root Post in Different Layers of Tooth: Linear vs Nonlinear Finite Element Stress Analysis

Rashmi V. Uddanwadiker,[1]* Pramod M. Padole,[1] and Harshwardhan Arya[2]

Mechanical Engineering Department, Visvesvaraya National Institute of Technology, Nagpur 440010, India[1] and D.K. Dental College, Hingna, Nagpur 441014, India[2]

Received 11 May 2007/Accepted 14 July 2007

The objective of this study was to obtain an accurate stress distribution pattern on different domains of a post- and core-treated tooth, taking into account the nonlinear properties of the periodontal ligament (PDL). Linear stress and deformation analysis was carried out using four posts, different in constitution and shape. Accurate three-dimensional models of a restored tooth with different layers were prepared using CAD modeling software. The study was carried out using a cast metal post and core assembly, a glass fiber, a carbon fiber, and a titanium post with a composite resin core. For each restoration, parallel, tapered and threaded posts were modeled. However, PDL exhibits nonlinear properties ensuring a uniform stress distribution in the tooth structure. Hence, accurate results could be expected by simulating the model for the nonlinear properties of PDL. Owing to computational difficulties, a simplified model was prepared in the ANSYS environment and nonlinear stress analysis was carried out. The results indicate that for optimum strength, rigidity and flexibility, tapered fiber posts with a composite resin core cemented to the root are desirable. Under similar loading conditions, in the case of nonlinear analysis, the stresses decreased by approximately 25% and the deformation increased by approximately 50% as compared with those in case of linear static analysis for an endodontically treated maxillary central incisor. Thus, stress distribution within the restored tooth and surrounding tissues can be better anticipated by a dentist. From the results of this study, the dimensions of a post could be modified, to further reduce stress in the oral cavity and thereby reduce the risk of root and post fractures.

[**Key words:** maxillary central incisor, multilinear elastic, post and core, fiber post, ANSYS workbench, nonlinear, finite element analysis, solid edge]

An endodontically restored tooth composed of different post and core materials produces different stress levels on the root, post and periodontal ligament (PDL) depending on the material used and the shape of the post. Sometimes, these stresses cause fracture of either the root post or the tooth root causing failure of tooth restoration. Therefore, it is important to study which restorative system is most stable under given loads. Researchers, to date, have used *in vitro* and *in vivo* tests to establish the suitability of different restoration methods (1–3). However, these methods are time consuming, costly, and cumbersome and yield only approximate results. Hence, finite element analysis was adopted for the analysis of structural stresses.

Finite element analysis is gaining acceptance because it is a rapid and an inexpensive method of investigating stress and strain patterns that could simulate the real life situations (4). This method closely simulates geometries, loads and material inhomogeneties. The basic steps involved in this method are preprocessing, processing and postprocessing. The preprocessing stage consists of geometric modeling of a structure, discretization of a model into smaller elements by the proper selection of an element type, and assigning the material properties. The elements are connected by nodes. The final step in preprocessing is the application of boundary conditions, that is, forces and displacement constraints are applied at specified nodes (5). Depending on the complexity of the model, computer software can process the discretized model in different stages. A set of simultaneous equations with thousands of variables are solved to achieve the desired results. The postprocessing stage consists of the graphical presentation of results. Typically, the deformed configurations, stress distributions at nodes and elements are computed and displayed at this stage.

Researchers who studied post and core restorations showed that posts with a high modulus of elasticity resulted in lower stresses (6). Post shapes had a relatively small impact on stress concentrations, whereas post materials introduced larger variations (7). The restorative material should have elasticity similar to that of dentin and the post should be inserted deeply to maintain a 5–6 mm gutta percha apical seal (8). The tooth and the surrounding tissues were assumed to be isotropic, homogenous, elastic and unsymmetrical in majority of the studies conducted related to stress analysis (9).

The PDL is a soft biological tissue that provides a firm bed for the tooth in the alveolar bone. It supports the tooth

* Corresponding author. e-mail: rashmiu71@rediffmail.com
phone: +91-9881239509 fax: +91-0712-2248205

during mastication and protects the alveolar bone and tooth root from damage. Since the modulus of elastic of the PDL is much smaller than those of the tooth and alveolar bone (10), the PDL undergoes the largest deformations when a force is applied to the tooth crown. Its material properties, therefore, mainly govern the mechanical properties of tooth deflection, which indicates a nonlinear force-deflection curve. The tooth is supported by the combined action of the periodontal ligament and alveolar bone. The PDL provides attachment of the tooth to the adjacent alveolar bone (11). It is a highly specialized connective tissue and is the most deformable tissue in the periodontal system, allowing tooth movements under functional loads.

This study was undertaken for a detailed stress analysis of an endodontically restored maxillary central incisor. The actual stresses produced by post and core restorations were investigated. Restorations using four different post and core materials and three different shapes were studied. The analysis was carried out in two stages; initially for a geometrically accurate model and later on for a simplified model. Stress analysis was carried out initially by assigning linear material properties to all the layers. Later on, the analysis was carried out by assigning nonlinear properties to PDL and linear properties to the remaining layers. Actual stresses observed would help in the optimum design of a post with due considerations to strength, rigidity, retention and resulting root fractures.

MATERIALS AND METHODS

The maxillary central incisor was selected for this study because it is a single-rooted tooth with a relatively simple anatomy and is highly susceptible to fracture. The original tooth and surrounding tissues were initially modeled with all the layers viz. enamel, dentin, pulp, PDL and bone and then the restored models were generated using the modeling software. The cementum layer was ignored for modeling purposes because its properties are similar to those of dentin (12). Hence, it was assumed to be merged with the dentin layer.

Accurate 3D modeling of restored tooth Three-dimensional models were prepared using CAD modeling software (Solid Edge ver. 15.0; Product Lifecycle Management solutions; Electronic Data System, Plano, TX, USA). The dimensions were obtained from Fig. 1, which shows the different views of the maxillary central incisor (13). A key point curve corresponding to the dentino-enamel junction was plotted by computing the 3D coordinates of different views using Microsoft Excel. The dentin layer was prepared with a proper ferrule of 2 mm dimension (14). The dentin was divided in two parts. The coronal part, which is below the ferrule, was treated as the core and the apical part was taken as the root with a length of 16 mm. The crown, with a length of 8 mm, was then modeled by taking the contours of the extracted tooth at different heights. Over the dentin, PDL was prepared by giving a suitable thickness of 0.18 mm to the outer surface of the dentin (15). The surface was converted to a solid for volumetric analysis. The bone was modeled with a free form. The post (16) was prepared on the apical facet of the core and volume was subtracted from the solid dentin part using Boolean algebra. A hollow root canal cavity of 1.1 mm diameter was created in the dentin for the insertion of the post. A small volume was removed from the root, 5 mm apical to the post, for gutta percha filling up to the apex (8). For the cast metal post and core restoration, the post and core were modeled as a single solid volume (17). However, for the remaining three restorations,

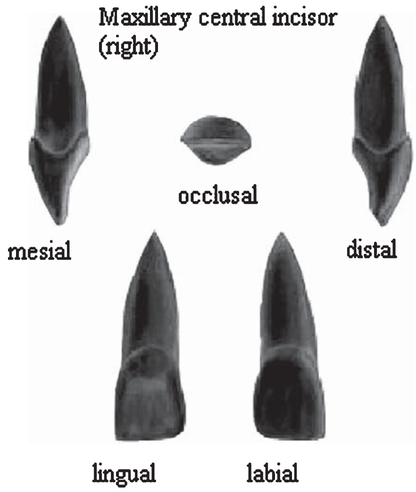

FIG. 1. Different views of central incisor. The views are labial, lingual, incisal, distal and mesial. These views were plotted on a graphing paper and 3D coordinates were obtained at different levels.

the post was modeled separately and one of its ends was inserted in the composite resin core (18). A taper was provided in the tapered post and a helical groove was cut on the surface of the threaded post.

A 50-μm-thin layer of a luting agent was also modeled between the core and the crown and in the post-dentin interface. Zinc phosphate, composite resin, and glass ionomer cements were used as luting agents. Zinc phosphate cement was used in the cast metal post and core assembly, because of its long working time; cement can be added directly to the canal prior to sealing the post to prevent air entrapment (19). Composite resin cement was used for the glass fiber post, carbon fiber post and titanium post for the root-post interface. Glass ionomer cement was used in the core-crown interface in all the restorations. Metal ceramic crowns were used for analysis. All the layers were then assembled in the assembly environment of Solid Edge software. Figure 2 shows the assembled and exploded models of a restored tooth with threaded, tapered, and parallel posts.

Linear analysis Linear analysis was initially carried out assuming linear properties that are specific values of modulus of elasticity, for all the layers of a tooth and the surrounding tissues, as shown Table 1.

ANSYS is computer-aided engineering design analysis software that enables finite element analysis. ANSYS ver. 9.0 (SAS IP, Canonsburg, PA, USA) was used. The assemblies created in the modeling environment were saved in ANSYS compatible file format (file *.sat, *i.e.*, save as text format), and were exported to ANSYS workbench environment to avoid data loss. Workbench is an integral part of the ANSYS suite of products. All the layers of the assembly were renamed and material properties were assigned.

A model was meshed with SOLID 187, CONTACT 174 and TARGET 170 element types. The solution parameters, such as total deformation and stresses were defined. The outer surface of the bone was constrained with zero degrees of freedom and the palatal surface of the tooth crown was given a load of 200 N at an angle of 130° with the long axis at the incisal edge. This load of 200 N is analogous to the load coming from the mandibular jaw central incisor to the maxillary jaw central incisor (6). The file thus created in ANSYS workbench was exported to the ANSYS 9.0 environment as *.inp (*i.e.*, input file) without any data loss. Now, the solution command was executed to obtain the results of the linear finite element analysis. Thus, preprocessing was carried out in Solid Edge and ANSYS workbench environments. Processing and postprocess-

TABLE 1. Material properties

No.	Material	Young's modulus (GPa)	Poisson's ratio	Reference
1	Dentin (root)	18.6	0.3	12
2	PDL	68.9e-3	0.4	10
3	Bone	13.7	0.3	12
4	Gutta percha (gp)	0.96e-3	0.4	10
5	Cast metal (post and core)	200	0.3	12
6	Titanium	120	0.3	10
7	Glass fiber post (matrix parallel to fiber)	50	0.3	10
8	Glass fiber post (matrix parallel to fiber)	9.62	0.33	10
9	Ceramic crown	96	0.3	10
10	Zinc phosphate cement	22.4	0.35	10
11	Carbon fiber post (matrix perpendicular to fiber)	9.62	0.33	12
12	Carbon Fiber post (matrix parallel to fiber)	129	0.33	12
13	Glass ionomer cement	04	0.35	10
14	Composite resin	22.2	0.24	12

ing were carried out using ANSYS 9.0 software.

3D modeling of geometrically simplified model Due to the limitations of the accurate model (as explained in the discussion), a simplified model was prepared. The dimensions for the geometrically simplified model were also obtained from Fig. 1. The geometry was assumed to be axisymmetric. As per the modeling steps in ANSYS, the key points were plotted from the coordinates. Lines were created from the key points and areas were created from lines. The areas corresponding to the bone, PDL, root, post, core and crown were then assigned with their corresponding material properties, that is, modulus of elasticity and Poisson's ratio, as shown in Table 1. However, the modulus of elasticity of PDL was taken as 0.17 MPa for linear analysis (20). This value was adopted because the Young's modulus of the linear model of the PDL fits the final stiffness (at 100% strain) of the nonlinear curve used for the nonlinear analysis.

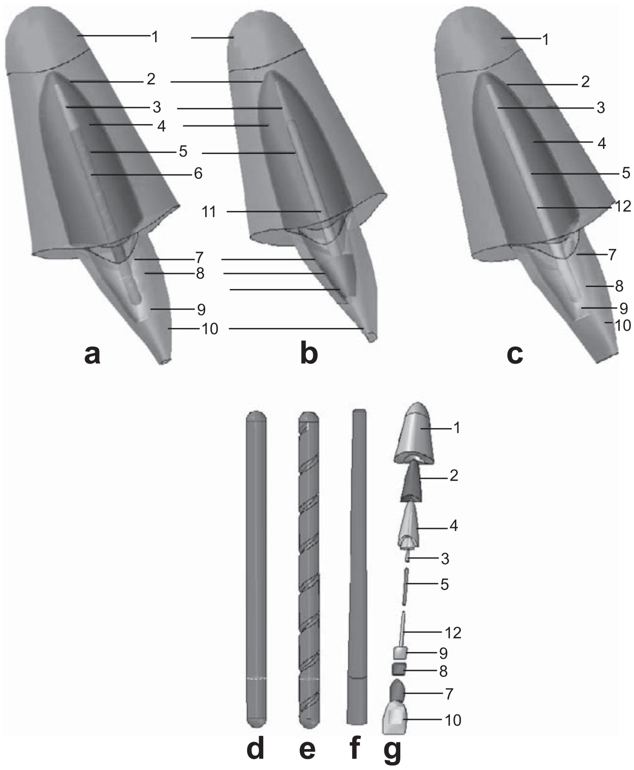

FIG. 2. Assembled model of restored tooth with threaded, tapered and parallel posts. (a–c) Assembly of the bone, PDL, root, gutta percha, post, core, crown, cement on the post and cement on the core layers. (a) Threaded titanium post with composite resin core; (b) cast-metal-tapered post and core; and (c) parallel sided post with a composite resin core assembly. Panels a and c show one end of the post inserted in core. Panel b shows a post and a core as a single assembly. (d) Parallel-sided post; (e) threaded post; and (f) tapered post. (g) Exploded view of tapered cast metal post and core assembly. 1, Bone; 2, periodontal ligament; 3, gutta percha; 4, dentin (root); 5, cement on post; 6, threaded post; 7, metal layer of crown; 8, cement on core; 9, core; 10, ceramic layer of crown; 11, tapered post; 12, parallel post.

Figure 3 shows a simplified model prepared using ANSYS software and the model with a load on the four nodes with their horizontal and vertical components and outer surface of the bone constrained. The model was meshed with the Plane 42 and the Solid 95 element type. The final mesh was created with 18,584 nodes and 10,916 elements. Initially, this geometrically simplified model was solved for linear analysis with static, linear and isotropic material properties and the results were obtained. This was carried out to compare the results of the linear and nonlinear analyses for the same model.

Steps for nonlinear analysis To carry out the nonlinear analysis, the PDL layer was assigned with multilinear elastic properties, as shown in Fig. 4 (20). In the compression, the PDL was de-

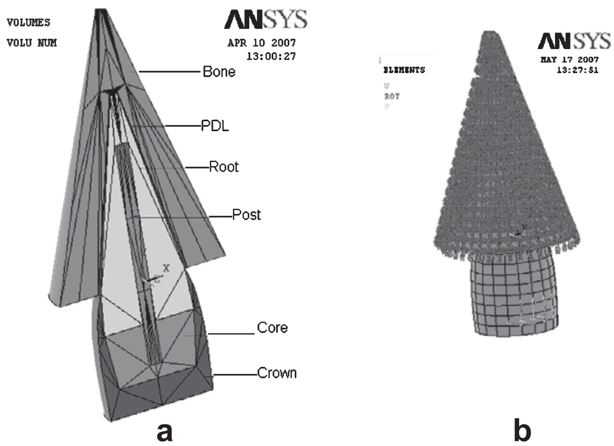

FIG. 3. Geometrically simplified model of restored tooth prepared in ANSYS. (a) Simplified model prepared for nonlinear analysis. The five layers are the bone, PDL, root, post and core, and crown. (b) Model loaded and constrained. A load of 200 N is distributed on the four nodes. The outer surface of the bone is constrained.

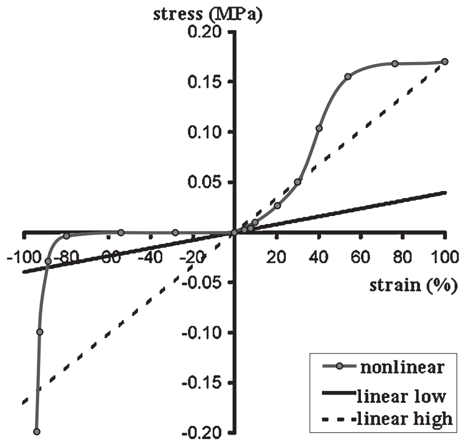

FIG. 4. Nonlinear stress strain curve for PDL. Stress is shown in MPa and strain in %.

scribed with a Young's modulus of 0.005 MPa up to the 93% strain level, after which a Young's modulus of 8.5 MPa was used to simulate precontact between the root and the surrounding bone. With tension, the Young's moduli gradually increased from 0.044 MPa at zero strain to 0.44 MPa at about 50% strain, after which a smaller Young's modulus of 0.032 MPa was used to simulate fiber disruption. The shape of the curve, with a low-stiffness toe region and a high-stiffness slope, closely resembles both experimentally (21) and mathematically determined relationships (22). The remaining parts were assigned with their corresponding linear properties.

The multilinear elastic material behavior option describes a conservative (path-independent) response in which unloading follows the same stress-strain path as loading. The load of 200 N distributed on four nodes was applied in ten small steps. The time stepping option was selected. The method of automatic time stepping is one in which the time step size and/or the applied loads are automatically determined in response to the current state of the analysis under consideration. An important point to be made here is that automatic loading always works through the adjustment of the time step size, and that the loads that are applied are automatically adjusted if ramped boundary conditions are activated. The minimum time step was selected as 0.2 and the maximum time step was 5. A total of 25 iterations were carried out for each step. The Newton Raphson (23) procedure was followed for the iterations.

The file was solved and the postprocessing command resulted into stresses and deformations at each step. Each step consumed 8–9 h of processing time.

RESULTS AND DISCUSSION

Table 2 shows the deformations on the different layers of the bone, PDL, dentin, post, core and crown for four restorations with different shapes of the post.

Importance of nonlinear analysis The majority of finite element problems solved by researchers in the past (7–10, 12) used linearity assumption. Deformations were assumed to be small and materials were assumed to be linear elastic. There exists a wide range of problems that exhibit material nonlinearity, that is, stresses and deflections are not directly proportional to load. These problems usually require iterative solution techniques. The Newton Raphson procedure is an iterative process of solving the nonlinear equation and it is needed to obtain a converged solution. The

TABLE 2. Deformation on different layers of cast metal, glass fiber, titanium, and carbon fiber post restoration

Layer	Parallel post	Tapered post	Threaded post
Cast metal			
Crown	0.417	0.721	0.665
Core	0.290	0.513	0.469
Post	0.290	0.513	0.469
Root	0.347	0.286	0.302
PDL	0.55	0.328	0.253
Bone	0.00783	0.00401	0.00382
Glass fiber			
Crown	0.671	0.687	0.686
Core	0.485	0.419	0.412
Post	0.409	0.492	0.491
Root	0.308	0.311	0.310
PDL	0.260	0.26	0.261
Bone	0.00385	0.00389	0.00387
Titanium			
Crown	0.962	0.685	0.684
Core	0.677	0.4910	0.490
Post	0.497	0.417	0.410
Root	0.363	0.309	0.309
PDL	0.261	0.259	0.259
Bone	0.00377	0.00388	0.00385
Carbon fiber			
Crown	0.682	0.684	0.683
Core	0.488	0.490	0.489
Post	0.409	0.416	0.409
Root	0.308	0.309	0.308
PDL	0.257	0.258	0.258
Bone	0.00386	0.00387	0.00384

maximum number of allowed equilibrium iterations should be performed to obtain convergence. The tooth restored in the oral cavity consists of an assembly of materials such as the bone, root, post, core, and crown with linear properties and layers such as PDL with nonlinear material properties. The stress analysis would give more realistic results if the nonlinear properties are assigned to the PDL layer. The properties of PDL are highly anisotropic and nonlinear; however, researchers have used different values of modulus of elasticity for PDL assuming linear elastic and isotropic behaviors. A 1997 report showed 17 publications in which E-moduli were used in finite element analysis (24). The values spanned 6 orders of magnitude ranging from 0.07 to 1750 MPa.

Thus, it was felt that the nonlinear and elastic nature of PDL would help in the uniform distribution of stresses in the bone and surrounding areas. Also, the intensity of stress will decrease considerably. To determine the precise effect of PDL on stress distribution, analysis should be carried out using the nonlinear material properties of PDL. The results showed that under similar loading conditions, in the case of the nonlinear analysis, the stresses decreased by approximately 25% and the deformation increased by approximately 50% as compared with those in the case of linear static analysis. The major portion of the load was shared by PDL, owing to its multilinear elastic property thereby protecting the endodontically treated tooth. This nonlinear behavior allows ligaments to permit initial deformation with minimum resistance. At higher forces, ligaments become stiffer, providing more resistance to increasing deformation. It is assumed that such stiffening protects the entire system. The effect of the nonlinearity of PDL could be discussed with respect to material type and shape of the post.

Limitations of geometrically accurate model for nonlinear analysis As explained earlier, the geometrically accurate model was prepared using Solid Edge software. The model was imported to the ANSYS workbench environment to avoid huge data loss. Furthermore, it was meshed in the same environment and the analysis was carried out in the ANSYS environment. However, in the case of the nonlinear analysis, it was observed that ANSYS workbench could not

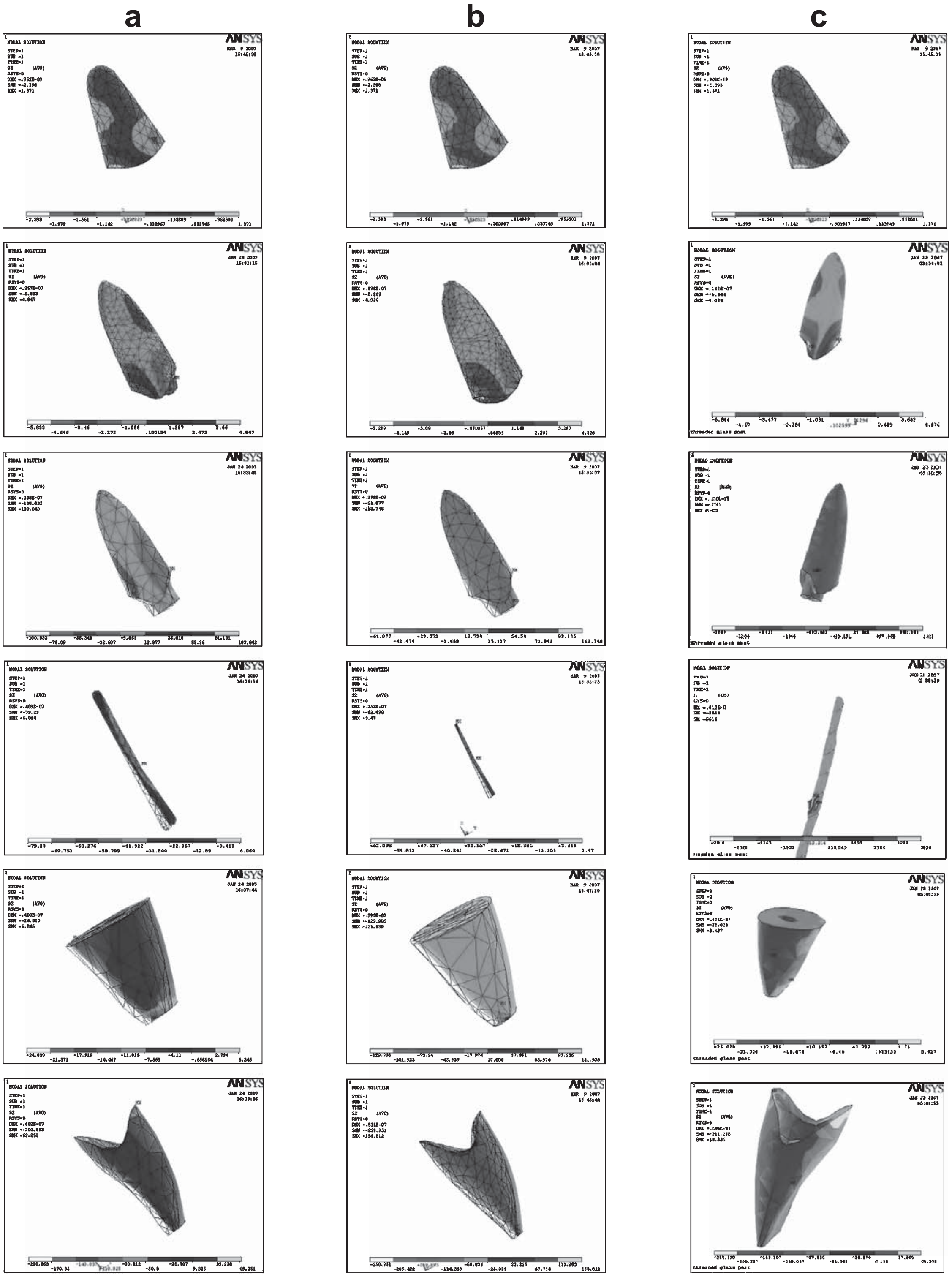

FIG. 5. Stresses for glass fiber restoration. The three figures show stresses along the axis developed on the bone, PDL, root, post, core and crown layers. Panels a, b, and c show axial stresses on the parallel-sided, tapered and threaded post, respectively.

mesh and create elements supporting the nonlinear analysis. Hence, it became necessary to model and mesh the geometry in the ANSYS environment with its limited modeling capabilities.

Note that for the geometrically simplified model, ANSYS software requires 4–5 h of processing. As the complexity of geometry increases, the processing time markedly increases. Owing to geometrical asymmetry and complicated contours, ANSYS software was unable to converge (5) the solution for the nonlinear analysis. Hence, a geometrically simplified 3D model was created in the ANSYS 9.0 environment with all the layers viz. bone, PDL, dentin, post, core and crown.

Selection of element type The geometrically accurate model was meshed with SOLID 187 (5) (which is a higher-order 3D 10-node element with quadratic displacement behavior), CONTACT 174 (used to represent contact and sliding between 3D target surfaces and a deformable surface) and TARGET 170 element types (used to represent various 3D target surfaces for the associated contact elements). The automesh option was selected in the workbench environment. This environment selects the most suitable element type depending on the geometry and material property assigned by the users.

For the simplified model, the areas were meshed with element type PLANE 42 (5). This is used for the 2D modeling of solid structures. The element can be used either as a plane element (plane stress or plane strain) or as an axisymmetric element. The element is defined by four nodes having two degrees of freedom at each node: translations in the nodal x- and y-directions. The meshed areas were rotated about the common axis using the extrude element option to create volumes with a SOLID 95 element type. This element can tolerate irregular shapes without much loss of accuracy. SOLID 95 is defined by 20 nodes having three degrees of freedom per node: translations in the nodal x-, y-, and z-directions. The element may have any spatial orientation. It has plasticity, creep, stress stiffening, a large deflection, and large strain capabilities. Thus, it is well suited for both linear and nonlinear analyses.

Material of post The results showed in Fig. 5a–c show higher stress levels in the coronal third of the roots on the facial surfaces. These results are also supported by the result of studies carried out previously (25). Unlike the other three restorations, in the cast metal post and core restoration, the post and core assembly was modeled as a single volume. Because the Young's modulus of this material is very high (200 MPa), the stresses developed in the root and post are relatively high, which may lead to both root and post fractures.

Figure 6 shows that the post material with a higher modulus of elasticity induces more stress on the post and less stress on the root. Because the Young's modulus of the glass fiber post is 50 GPa and that of the titanium posts is 120 GPa, the stresses on the root are maximum for the glass fiber post restoration and minimum for the titanium post restoration. Previous studies indicated that stresses were reduced with an increase in modulus of elasticity (6, 26).

However, it was established in this research that stresses are further reduced by 25% as determined by nonlinear analysis (Fig. 7). Thus, the overall stresses developed in the post

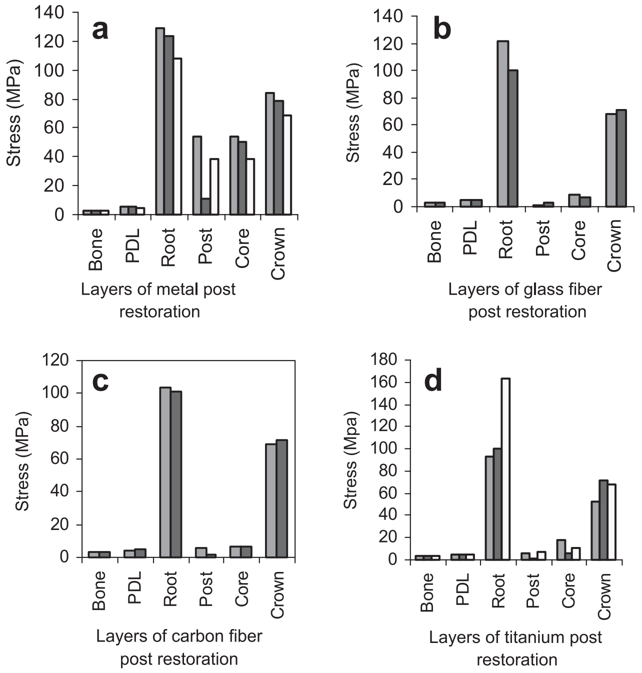

FIG. 6. Axial stresses on different layers of restoration. Graphs a–d show a comparison of stresses for the different domains of the tooth for different shapes of (a) the cast metal post, (b) glass fiber post, (c) carbon fiber post and (d) titanium post restoration. The threading in the fiber post is not feasible and hence stress values obtained using fiber posts are not considered for graphical comparison. Bars: light grey, parallel post; dark grey, tapered post; white, threaded post.

and root would be further reduced thereby decreasing the chances of post and root fractures.

The deformation results (Table 2) show that minimum deformation is obtained in the carbon and glass fiber post restorations, whereas the cast metal post restoration shows maximum deformation. The flexibility of the post material is desirable. Because the flexibilities of the cast metal and titanium are low, there are chances of post failure. It has been suggested that more stiff systems work against the natural function of a tooth (27).

It has been suggested that the flexibility of the post-core system induced lower stresses on the root structure and consequently a lower risk of root fracture (28). Concerning the material of the post, a smaller incidence of extensive fractures in teeth restored using carbon fiber posts (40%) was found, whereas the same kinds of fracture were observed in 100% of cases of teeth restored using cast metal posts. Researchers observed only 5% root fractures in teeth restored using carbon fiber posts, the remaining 95% being due to the displacement of the posts or core or the whole system. As for the metallic posts, 91% root fractures were verified. These results suggest that posts made of composite materials are capable of reducing to the minimum, the risk of root fracture.

Shape of post The threaded post induced high stress levels in the post and root as expected. The stresses were concentrated at the crest and the root of the helical groove. The stress induced by the tapered post was slightly lower than the stress induced by the parallel post. The computer

TABLE 3. Data for linear analysis vs nonlinear analysis

Restoration	Cast metal post and core		Glass fiberpost		Carbon fiberpost		Titanium post	
	Linear	Non linear	Linear	Non linear	Linear	Non linear	Linear	Non linear
Deformation (mm)	0.212	0.311	0.393	0.59	0.199	0.312	0.201	0.315
Stress (MPa)	73.49	56.72	60.52	37.22	67.37	45.61	71.16	47.09

model of the threaded fiber post was created for study purpose only but is not practically feasible. The fiber post cannot be threaded owing to its material characteristics. Hence these results were not discussed.

These results could be validated with available *in vitro* and *in vivo* results, which also suggest that the number of root fractures is larger when using a threaded post (28). Post and core failures also take place owing to the loosening of the post. Studies suggested that threaded posts are the most retentive followed by parallel posts; tapered posts are the least retentive. Thus, a tapered post with a minimum taper is the best design that induces comparatively lower stress and better retention.

The chances of post loosening are high due to stresses applied on it. PDL is responsible for damping effects that could dissipate the high stress concentration levels, owing to its characteristic material properties. Hence, if the stresses produced are low, the retention would be better. Thus, the presence of PDL ensures a uniform distribution of stresses in the tooth and surrounding tissues, thereby reducing the risk of root fracture.

From the result of our study of the linear analysis of a geometrically accurate model, we conclude that tapered fiber posts with a composite resin core cemented to the root provide optimum strength, rigidity and flexibility. In the future, all studies of stress analysis should consider the nonlinear properties of PDL, which can reduce stress in the oral cavity and thereby reduce the risk of root and post fractures.

We believe that even if the results obtained using the proposed model may not be absolutely accurate at this stage, this model represents a starting point and, more specifically, it might enable the analysis of stress and strain states closer to reality than those that have been computed so far. This feeling is justified by the fact that in this study, a geometrical model that provides results closer to the experimental evidence than to that adopted so far has been formulated and adopted.

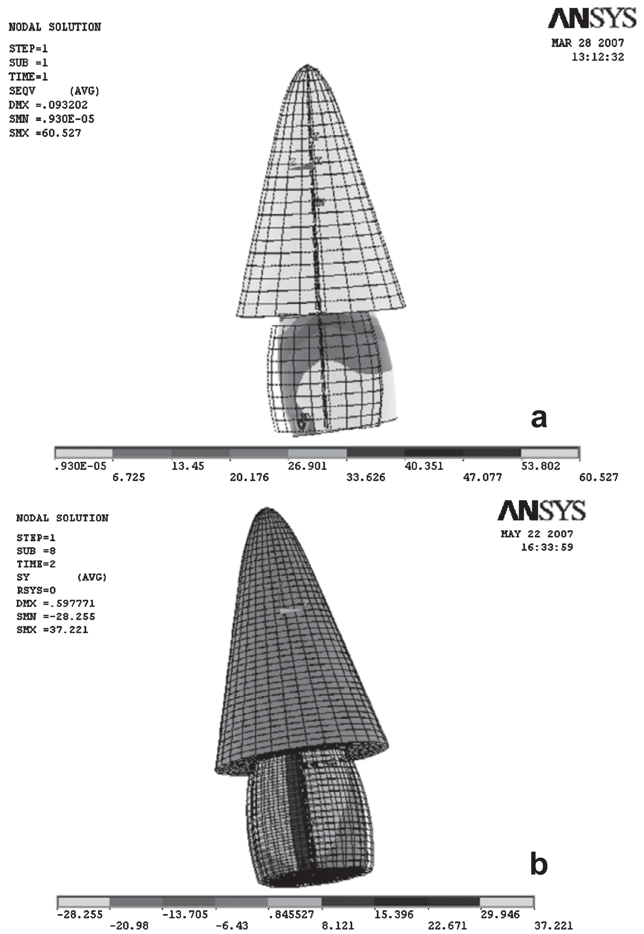

FIG. 7. Axial stresses on geometrically simplified assembly of restored maxillary central incisor: (a) linear analysis and (b) nonlinear analysis. Deformed and undeformed shapes of the crown are also shown.

ACKNOWLEDGMENTS

The authors sincerely wish to thank Dysmech Consultancy services for their effort in helping out in the preparation of the 3D model. Thanks are due to Government Dental College for providing the data required for this research study. Special thanks to Dr. B. S. Arya, senior orthodontist for his continuous support and guidance and Mr. Manish Dhoke for assistance with finite element analysis.

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