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Effect of Non Linearity of PDL on a Restored Tooth

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Abstract - *To obtain an accurate stress distribution pattern of the restored tooth, taking into account non linear properties of Periodontal Ligament (PDL), linear stress and deformation analysis was carried out with four posts, different in constitution and shape. However, as the PDL exhibits non linear behaviour, more accurate results could be expected by simulating the model for non linear properties of PDL. Due to computational difficulties, a simplified model was prepared and non linear stress analysis was carried out. In case of non linear analysis the stresses were decreased by 25% and deformation was increased by 50% approximately as compared to linear static analysis of the restored maxillary central incisor.*

KEY WORDS: Maxillary central incisor, ANSYS workbench, Non linear, Finite element analysis, Solid Edge

INTRODUCTION

The endodontically restored tooth with different post and core materials produce different stress levels on the root, post and periodontal ligament (PDL) depending upon the material and the shape of the post. Sometimes these stresses cause fracture of either the root post or the tooth root causing failure of the restoration. Therefore, it is important to study which restorative system is most durable under given loads.

Researchers previously used *in-vitro* and *in-vivo* testing to establish the suitability of different restorations (1-3). However, these methods are time consuming, costly, cumbersome and yield approximate results. Finite element analysis offers an alternative for the study of structural stresses.

This is gaining acceptance because it is a rapid and inexpensive way to investigate stress and strain patterns which may simulate the real life situation (4). This method may closely simulate geometries, loads and material inhomogeneties. The basic steps involved in this method are Preprocessing, Processing and Post-processing. The preprocessing consists of geometric modeling of structure, discretization of model into smaller elements by proper selection of element type, and assigning the material properties. The elements are connected by nodes. The final step in preprocessing is the application of boundary conditions i.e. forces and displacement constraints are applied at specified nodes (5). Depending upon 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 post processing stage deals with the graphical presentation of results. Typically the deformed configurations, stress distribution at nodes and elements are computed and displayed at this stage.

Researchers who studied the post and core restorations reported that posts with higher modulus of elasticity resulted in lower stresses (6). Post shapes had relatively small impact on the stress concentrations while post materials introduced higher variations (7). The restorative material should have elasticity similar to dentin and the post should be inserted deeply maintaining 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 studies related to stress analysis (9).

The periodontal ligament is the biological tissue that provides a firm bed for the tooth in the alveolar bone. It supports the tooth during mastication and protects the alveolar bone and the tooth root from damage. Since the elastic modulus of the PDL is much lower than that 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 for tooth movements under functional loads.

The present study was undertaken for detailed stress analysis of endodontically restored maxillary central incisor. The actual stresses produced due to post and core restoration were investigated. Restorations with 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 non linear properties to PDL and linear properties to the remaining layers. Actual stresses observed would help in the optimum design of post with due considerations to strength, rigidity, retention and resultant root fractures.

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MATERIALS AND METHODS

The maxillary central incisor was selected for the present study because it is a single rooted tooth with relatively simple anatomy and is highly susceptible to fracture. The original tooth and the 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 purpose since its properties are similar to that of dentin (12). Hence, it was assumed to be merged with dentin layer.

Accurate 3D modeling of Restored tooth

Three Dimensional models were prepared using CAD modeling software, Solid Edge 15.0 version (PLM Solutions; Electronic Data System Corporation, U.S.). The dimensions were obtained from Fig.1 which shows the different views of the maxillary central incisor (13). A key point curve corresponding to dentino-enamel junction was plotted by computing the 3D coordinates of different views using Microsoft excel program. The dentin layer was prepared with a ferrule of 2 mm dimension (14). The dentin was divided in two parts. The coronal part, below the ferrule, was treated as the core and the apical part was taken as root of length 16 mm. The crown, of length 8 mm, was then modeled by taking the contours of the extracted tooth at different heights. Over the dentin, PDL was prepared by giving suitable thickness of 0.18 mm to the outer surface of the dentin (15). The surface was converted to solid for the volumetric analysis purpose. The bone was modeled with free form. The post (16) was prepared on the apical facet of the core and that 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 post. A small volume was removed from the root, 5 mm apical to the post, for Gutta percha filling up to the apex (8). The cast metal post and core restoration was modeled as a single solid volume (17). But for the remaining three restorations, the post was modeled separately with the coronal end 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 threaded post.

A 50 micron thin layer of luting agent was also modeled between core and 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 cast metal post and core because with its longer working time, cement can be added directly to the canal prior to seating the post to prevent air entrapment (19). Composite resin cement was used for the glass fiber post, carbon fiber post and titanium post. 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 the Solid Edge software. Figure 2 shows assembled and exploded model of restored tooth with threaded, tapered, and parallel post respectively.

Linear Analysis

Linear analysis was initially carried out assuming linear properties, that is, specific value of modulus of elasticity, for all the layers of tooth and surrounding tissues as per Table 1.

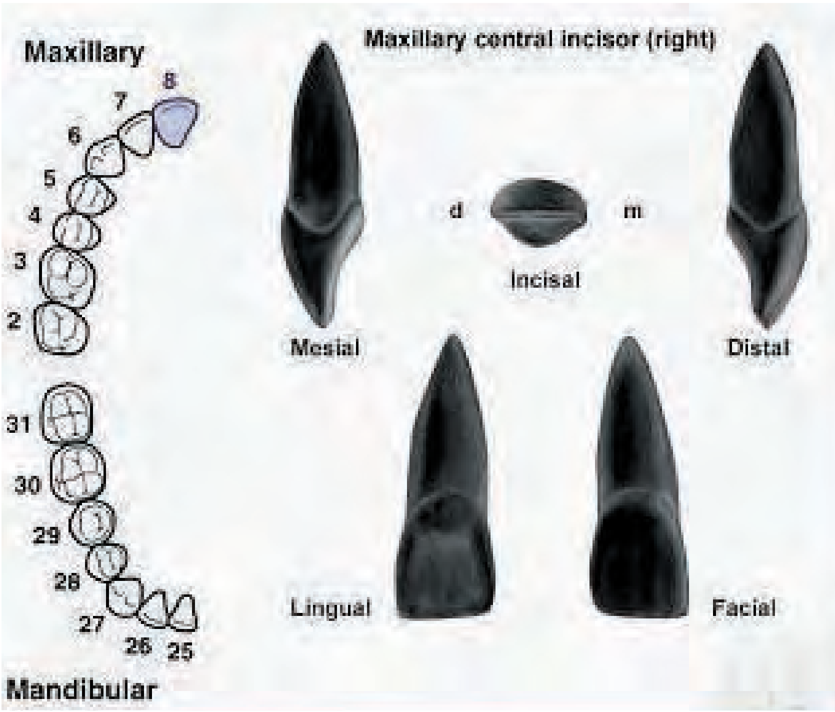

Figure 1. *Different views of Central Incisor. This figure shows the different views of the maxillary central incisor. The views are labial, lingual, incisal, distal and mesial. These views were plotted on graph paper and the 3 D coordinates were obtained at different levels.*

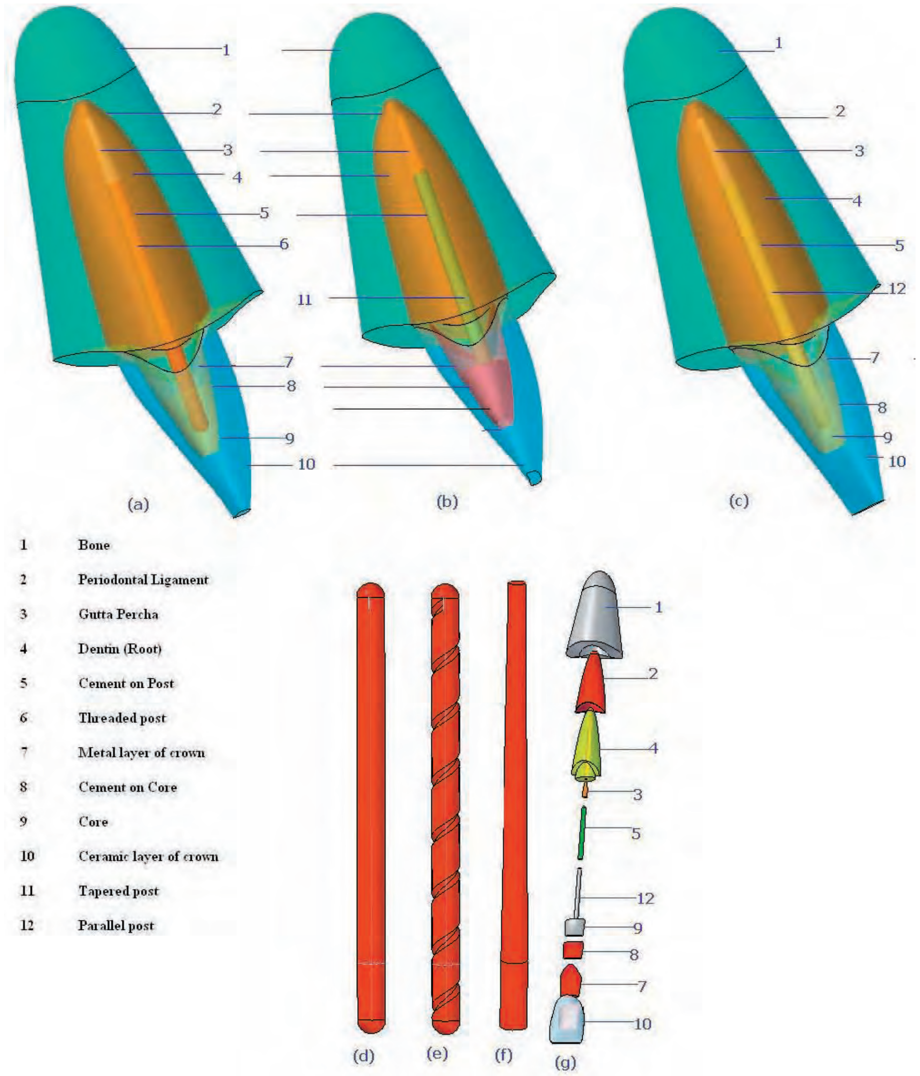

Figure 2. *Assembled model of restored tooth with threaded post, tapered post and parallel post. The three figures show the assembled view of restored tooth. It shows assembly of bone, PDL, root, gutta percha, post, core, crown, cement on post and cement on core layers. The figures (a) (b) and (c) show threaded titanium post with composite resin core, cast metal tapered post and core and parallel sided post with composite resin core assembly respectively. Figures (a) and (c) show one end of the post inserted in core. Figure (b) shows post and core as single assembly. Figures (d), (e), and (f) show parallel sided post, threaded post and tapered post. Figure (g) shows exploded view of tapered cast metal post and core assembly.*

Table 1. *Material Properties (10, 12)*

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

ANSYS is computer-aided engineering design analysis software which enables finite element analysis. ANSYS 9.0 version of Ansys Inc., (SAS IP Inc.) was used. The assemblies created in the modeling environment were saved as 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 re-named and material properties were assigned.

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 degrees 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 Ansys 9.0 environment to undertake linear finite element analysis.

Thus, preprocessing was done with Solid Edge and Ansys workbench environment. Processing and post processing was carried out using Ansys 9.0 software.

3D modeling of geometrically simplified model

Due to the limitations of the accurate model (as explained in 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 axi-symmetric. 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 bone, PDL, root, post, core and crown were then assigned with their corresponding material properties i.e. modulus of elasticity and Poisson's ratio as listed 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 non-linear curve used for non linear analysis.

Figure 3 shows simplified model prepared in ANSYS Software and the model with load on four nodes with their horizontal and vertical components and outer surface of bone constrained. The model was meshed with Plane 42 and Solid 95 element type. The final mesh was created with 18584 nodes and 10916 elements.

Initially, this geometrically simplified model was solved for linear analysis with static, linear, isotropic material properties and the results were obtained. This was done to compare the results of linear and non linear analysis for same model.

Steps in Non Linear Analysis

For carrying out the non linear analysis the PDL layer was assigned with multi linear elastic properties as shown in Fig. 4 (20). In compression, the PDL was described 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 pre-contact between the roots and the surrounding bone. In tension, the Young's moduli gradually increased from 0.044 MPa at zero strain level 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 Multi-linear 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.

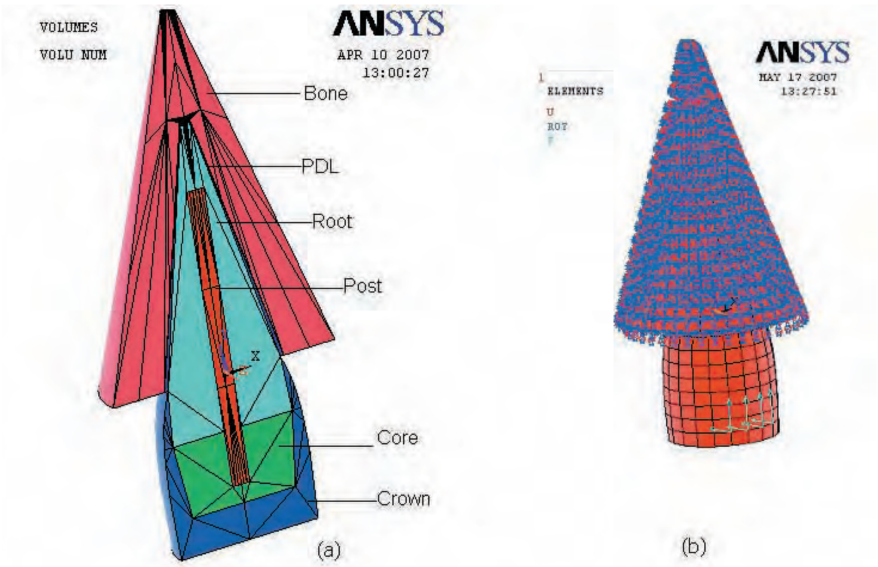

Figure 3. *Geometrically simplified model of restored tooth prepared in Ansys . The figure 3(a) shows simplified model prepared for non linear analysis purpose. The five layers are bone, PDL, root, post & core and crown. Figure 3(b) shows a model loaded and constrained. Load of 200 N is distributed on four nodes. Outer surface of the bone is constrained.*

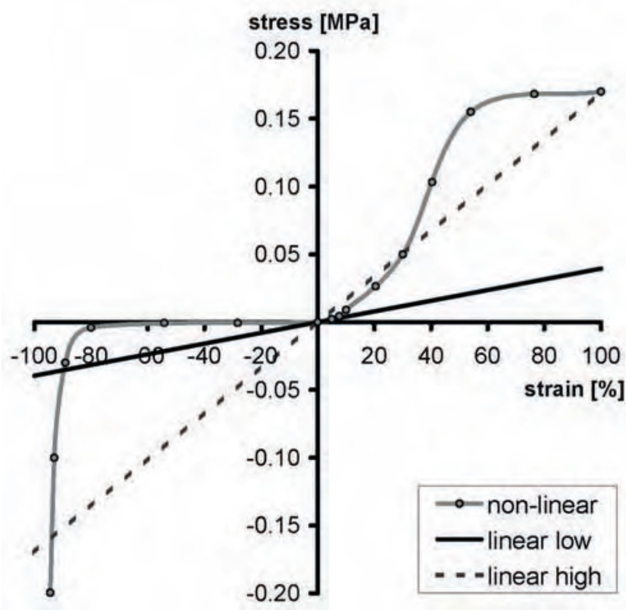

Figure 4. *Non linear stress strain curve for PDL (20). The curve represents non linear properties of stress strain assigned to PDL layer. The stresses are shown in MPa and strains in %.*

Table 2 (a). *Deformation on Different layers of Cast Metal post restoration*

Layer	*Parallel Post*	*Tapered Post*	*Threaded Post*
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

Table 2 (b). *Deformation on Different layers of Glass Fiber post restoration*

Layer	*Parallel Post*	*Tapered Post*	*Threaded Post*
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

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. Minimum time step was selected as 0.2 and maximum time step was 5. Total 25 iterations were carried out for each step. Newton Raphson (23) procedure was followed for iterations.

The file was solved and post processing command resulted into stresses and deformations at each step. Each step consumed 8-9 hours of processing time.

Table 2 (c). *Deformation on Different layers of Titanium post restoration*

Layer	*Parallel Post*	*Tapered Post*	*Threaded Post*
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

Table 2 (d). *Deformation on Different layers of Carbon Fiber post restoration*

Layer	*Parallel Post*	*Tapered Post*	*Threaded Post*
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

RESULTS

The results obtained from the linear analysis of the accurate 3D model are as shown in the Fig. 5. The results in the Fig. 6 show variation of axial deformation within a tooth due to change in geometry and material of the post. The Tables 2 (a) to 2 (d) shows the deformations on the different layers of bone, PDL, dentin, post, core and crown for four restorations with different shapes of the post.

For the simplified model, the linear and non linear stresses and the deformations were compared. Table 3 gives the comparison of linear and non linear stresses. The results from Ansys are shown in Fig. 7.

DISCUSSION

Importance of Non Linear analysis

A majority of finite element problems solved by researchers in the past (7, 8, 9, 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 non linearity i.e. stresses and deflections are not directly proportional to load. These problems usually require iterative solution techniques. The Newton Raphson procedure is an iterative process for solving the non linear equation and it is needed to obtain a converged solution. The maximum number of allowed equilibrium iterations should be performed in order to obtain convergence. The tooth restored in the oral cavity consists of an assembly of materials like bone, root,

Table 3. *Data for Linear analysis vs. Non linear analysis*

Restoration	*Cast Metal Post and Core*		*Glass Fiber Post*		*Carbon fiber Post*		*Titanium Post*	
	Linear	*Non Liear*	*Linear*	*Non Liear*	*Linear*	*Non Liear*	*Linear*	*Non Liear*
Deformation(mm)	0.212	0.311	0.393	0.59	0.199	0.312	0.201	0.315
Stresses(MPa)	73.49	56.72	60.52	37.22	67.37	45.61	71.16	47.09

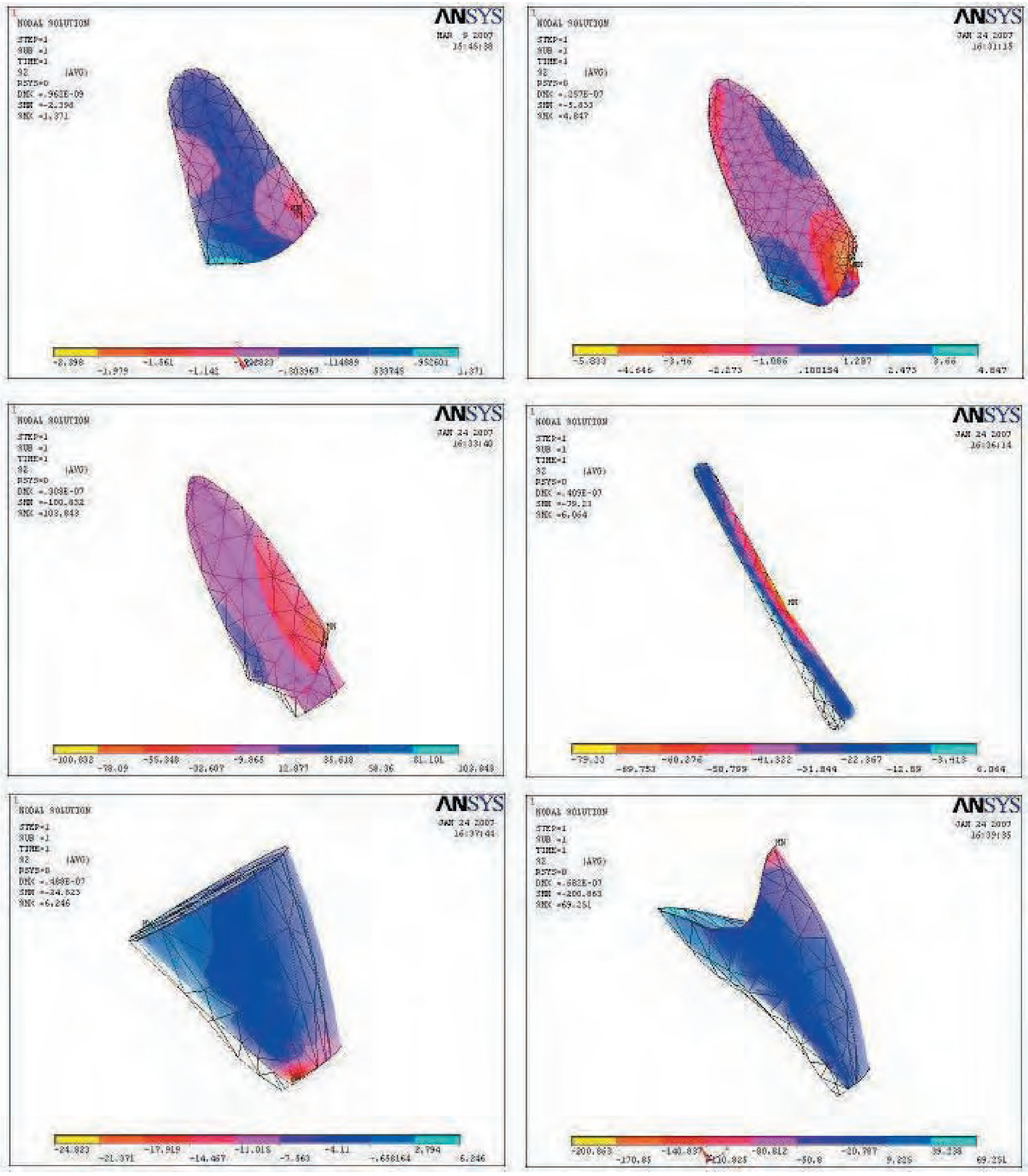

Figure 5(a). *Stresses of parallel post for Carbon fiber restoration*

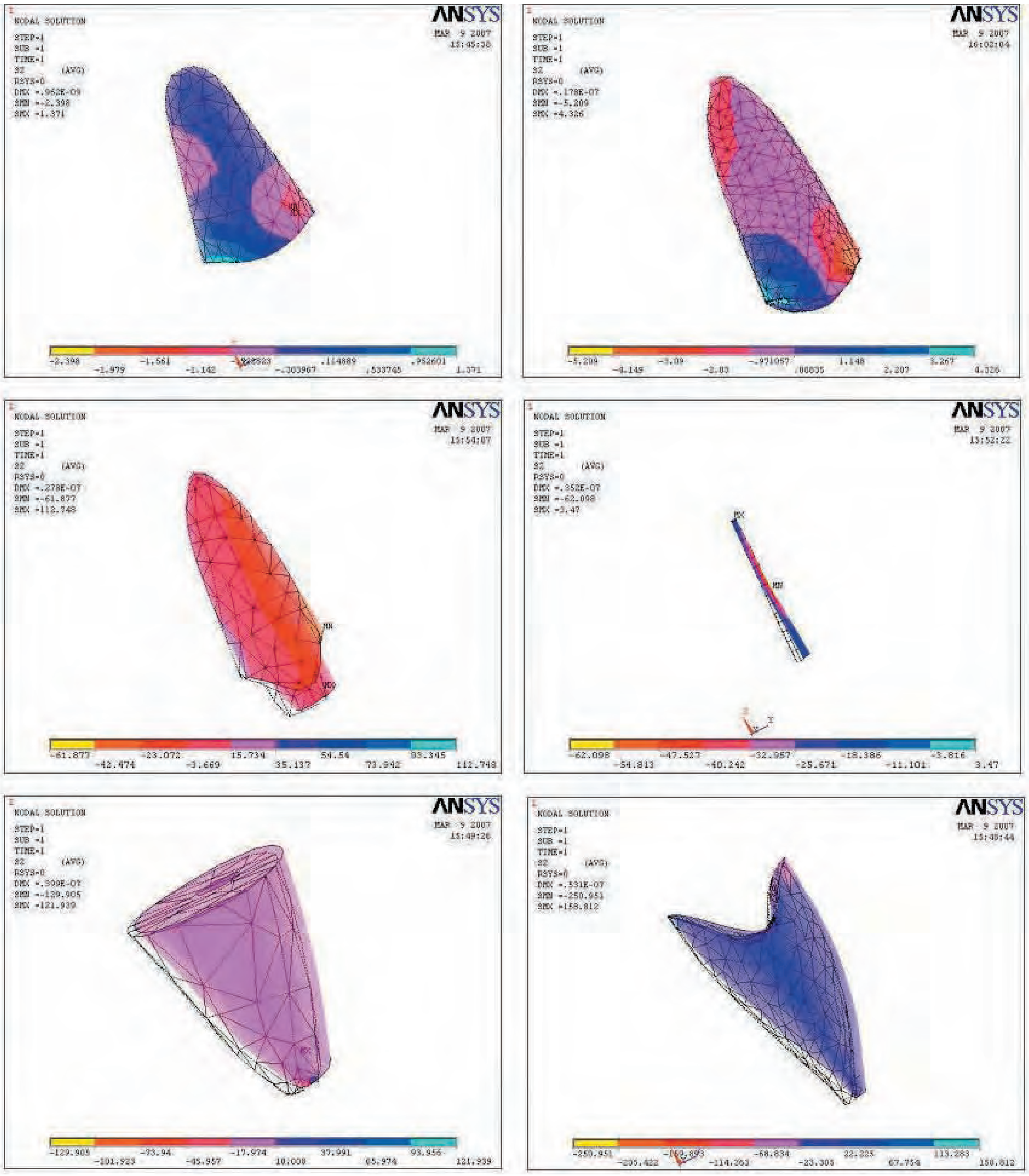

Figure 5(b). *Stresses on tapered post for glass fiber restoration*

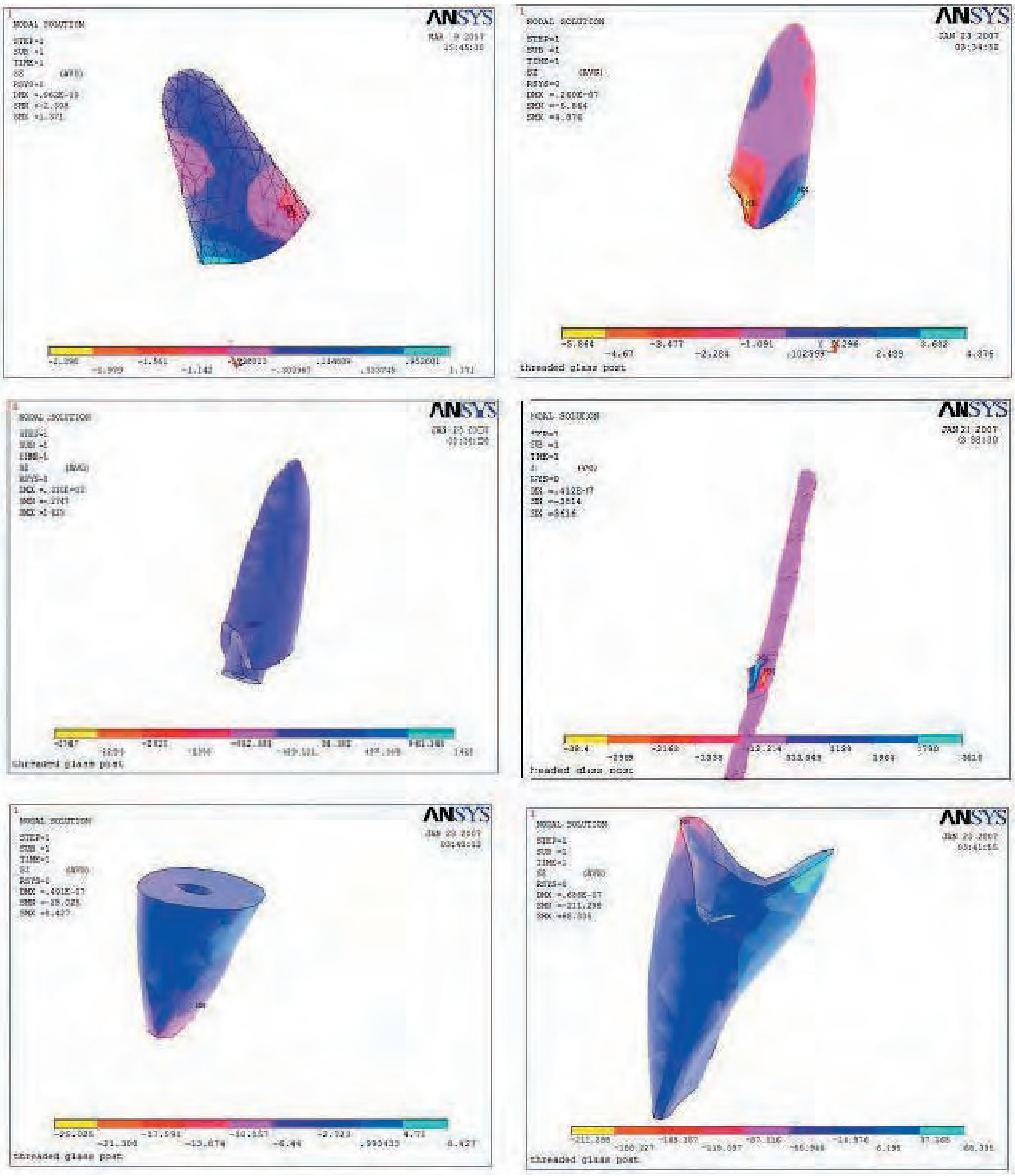

Figure 5(c). *Stresses on threaded post for Titanium post restoration*

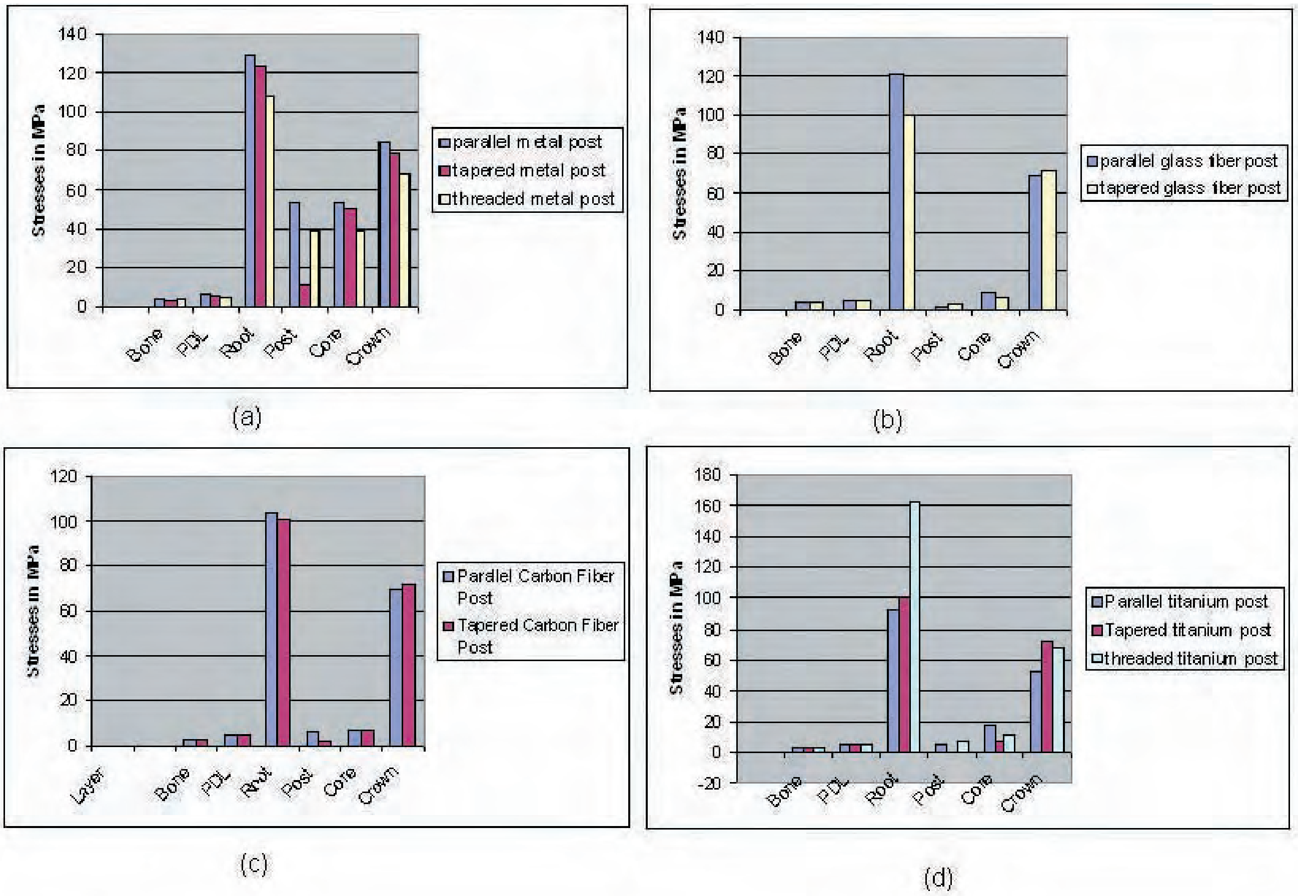

Figure 6. *Axial Stresses on Different layers of restoration. The graph (a), (b), (c), and (d) show the comparison of stresses for the different domains of the tooth for different shapes of the cast metal post, glass fiber post, carbon fiber post and titanium post restoration. The threading in the fiber post is not feasible and hence those values are not taken into account.*

post, core, and crown with linear properties and PDL with non linear material properties. The stress analysis would give more realistic results if the non linear properties are assigned to the PDL layer. The properties of the PDL are highly anisotropic and non linear. However, researchers have used different values of modulus of elasticity for PDL assuming linear elastic and isotropic behavior. A 1997 report listed 17 publications in which E-moduli were used in finite element analyses (24). The values spanned 6 orders of magnitude ranging from 0.07 to 1750 MPa.

Thus, it was felt that the non linear and elastic nature of PDL would help in uniform distribution of stresses in the bone and the surrounding area. Also the intensity of stress will reduce considerably. To obtain precise effect of PDL on the stress distribution, analysis should be carried out with non linear material properties of PDL.

The results indicated that under similar loading conditions, in case of non linear analysis the stresses were decreased by 25% and the deformation was increased by 50% approximately as compared to linear static analysis. The major portion of the load was shared by the PDL, due to its multi linear elastic property; thereby protecting the endodontically treated tooth. This non linear 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. Effect of non linearity of PDL could be discussed with respect to material and shape of the post.

Limitations of geometrically accurate model for Non Linear analysis

As explained earlier, the geometrically accurate model was prepared in Solid Edge software. The model was imported to ANSYS workbench environment to avoid huge data loss. Further, it was meshed in the same environment and the analysis was carried out in ANSYS environment. However, in case of non linear analysis, it was observed that ANSYS workbench could not mesh and create elements supporting the non linear analysis. Hence, it became necessary to model and mesh the geometry in ANSYS environment with its limited modeling capabilities.

It is worth mentioning that for geometrically simplified model ANSYS software requires 4-5 hours of processing. As the complexity of geometry increases the processing time increases drastically. Due to geometrical asymmetry and complicated contours, the ANSYS software was unable to converge (5) the solution for non-linear analysis. Hence, a geometrically simplified 3D model was created in ANSYS 9.0 Environment with all the layers viz. Bone, PDL, Dentin, post, core and crown.

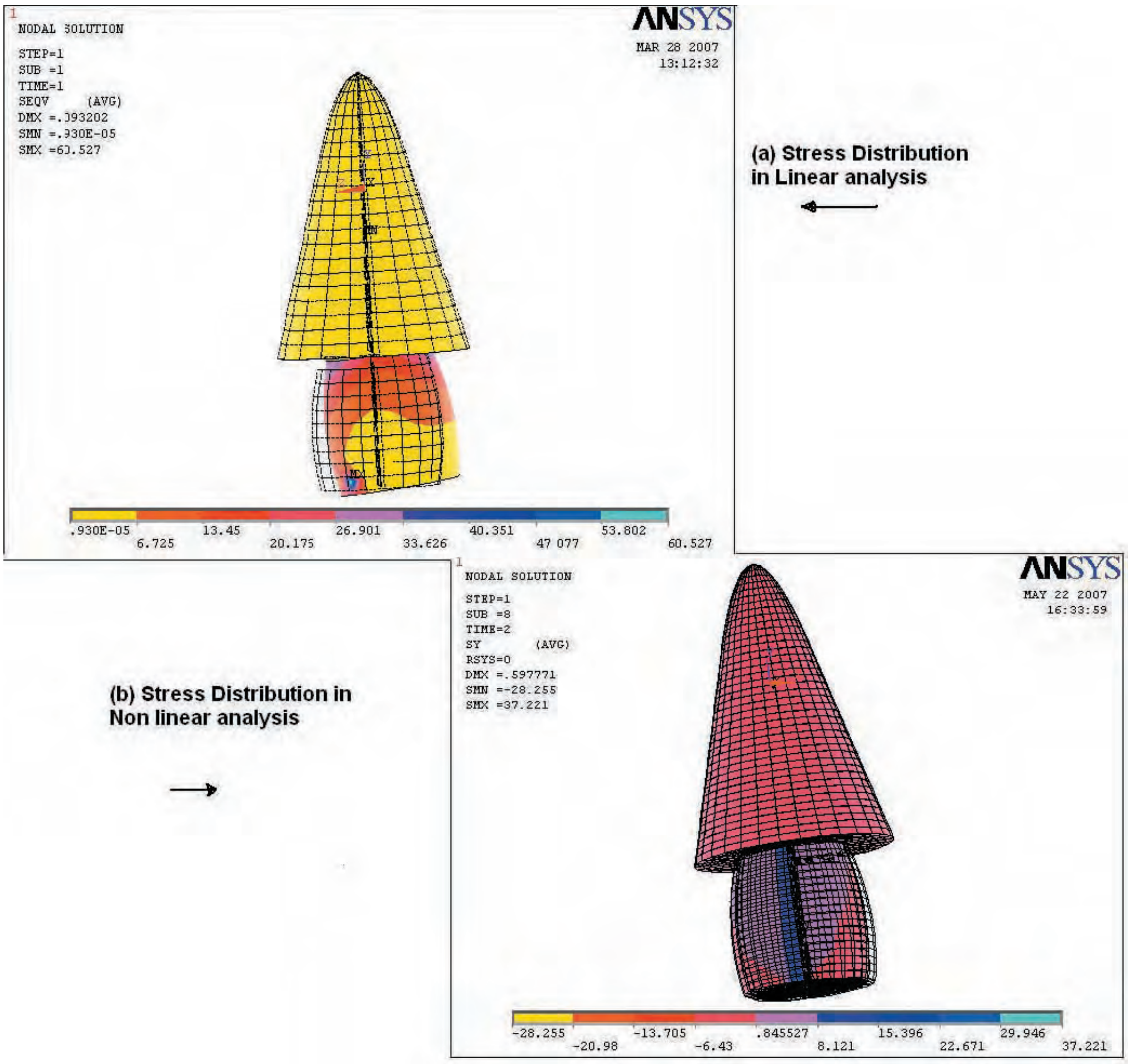

Figure 7. *Axial stresses on geometrically simplified assembly (a) linear analysis (b) Non linear analysis. Figure shows the results of linear analysis and non linear analysis for the simplified model of restored maxillary central incisor. Deformed and un-deformed shapes of crown are also shown*

Selection of element type

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

For the simplified model the areas were meshed with element type PLANE 42 (5). It is used for 2-D modeling of solid structures. The element can be used either as a plane element (plane stress or plane strain) or as an axi-symmetric 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 with the extrude element option to create volumes with SOLID 95 element type. This element can tolerate irregular shapes without as much loss of accuracy. It 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, large deflection, and large strain capabilities. Thus, it is well suited for both linear and non linear analysis.

Material of the post

The results in the Fig. 5(a) to 5(c) show the higher stress levels in the coronal third of the roots on facial surfaces. These results are also supported by the studies carried out in recent past (25).

Unlike the other three restorations, in the cast metal post and core restoration, the post and core was modeled as a single volume. Since the value of Young's modulus of this material is very high (200 MPa), the stresses developed in root and post are quite high which may lead to both root and post fractures.

Figure 6 indicates that post material with higher modulus of elasticity induces more stresses on post and lesser stresses on root. Since, the value of Young's modulus for glass fiber post is 50GPa, and for titanium posts 120 GPa, hence, the stresses on the root are maximum for glass fiber post restoration and minimum for the restoration with titanium post. 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 % with non linear analysis (Fig. 7). Thus, the overall stresses developed in the post and the root would be further reduced thereby decreasing the chances of post and root fracture.

The deformation results (Table 2) show that minimum deformation is obtained in carbon and glass fiber post restoration whereas the cast metal post has maximum deformation. The flexibility of the post material is desirable. Since the flexibility of cast metal and titanium is very less, there are chances of post failure. It has been suggested that the stiff systems have been evaluated to work against the natural function of the tooth (27).

Literature (28) suggested that flexible post-core systems induced lesser stresses on the root structure and consequently smaller risk of root fracture. Concerning the material of the post, smaller incidence of extensive fractures in teeth restored with carbon fiber posts (40%) was found, while the same kind of fractures were observed in 100% of the cases of teeth restored with cast metal posts. Researchers observed only 5% of root fractures in teeth restored with carbon fiber posts, being the remaining 95% due to the displacement of the posts or of the core or of the whole system. Yet for the metallic posts, 91% of root fractures were verified.

These results established the fact that the posts made of composite materials minimised risk of root fracture

Shape of the post

The threaded post induced high stress levels in the post and the root as expected. The stresses were concentrated at the crest and the root of the helical groove. The stresses due to tapered and parallel posts when compared show slightly lower stresses in the former. The fiber post can not be threaded due to its material characteristics. Hence those results were not discussed.

These results could be validated with available *in vitro* and *in vivo* results, which also suggested that root fractures were greater with threaded post (28). Post and core failure also take place due to loosening of the post. Studies suggested that threaded posts are most retentive followed by parallel post; tapered posts are least retentive. Thus, tapered post with minimum taper is the most optimum design with comparatively lesser stresses and better retention.

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

CONCLUSION

The study of linear analysis of geometrically accurate model concluded that tapered fiber posts with composite resin core cemented to the root are desirable for optimum strength, rigidity and flexibility. In future all the studies of stress analysis should consider non linear properties of the PDL, which can reduce the stresses in the oral cavity and thereby reduce the risk of root and post fracture.

Authors feel that even if the results given by the proposed model may not be judged as absolutely accurate at the present stage of the knowledge. This model should represent a starting point and, more specifically, it might enable the analyst to obtain stress and strain states closer to “reality” than those computed so far. This feeling is justified by the fact that in this study a geometrical model closer to the experimental evidence has been formulated and employed than those adopted so far.

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