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3D FEA of cemented steel, glass and carbon posts in a maxillary incisor

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Summary *Objectives.* A comparative study on the stress distribution in the dentine and cement layer of an endodontically treated maxillary incisor has been carried out by using Finite Element Analysis (FEA). The role of post and cement rigidity on reliability of endodontic restorations is discussed.

Methods. A 3D FEM model (13,272 elements and 15,152 nodes) of a central maxillary incisor is presented. A chewing static force of 10 N was applied at 125° angle with the tooth longitudinal axis at the palatal surface of the crown. Steel, carbon and glass fiber posts have been considered. The differences in occlusal load transfer ability when steel, carbon and glass posts, fixed to root canal using luting cements of different elastic moduli (7.0 and 18.7 GPa) are discussed.

Results and significance. The more stiff systems (steel and carbon posts) have been evaluated to work against the natural function of the tooth. Maximum Von Mises equivalent stress values ranging from 7.5 (steel) to 5.4 and 3.6 MPa (respectively, for carbon posts fixed with high and low cement moduli) and to 2.2 MPa (either for glass posts fixed with high and low cement moduli) have been observed under a static masticatory load of 10 N. A very stiff post works against the natural function of the tooth creating zones of tension and shear both in the dentine and at the interfaces of the luting cement and the post. Stresses in static loading do not reach material (dentine and cement) failure limits, however, they significantly differ leading to different abilities of the restored systems to sustain fatigue loading. The influence of the cement layer elasticity in redistributing the stresses has been observed to be less relevant as the post flexibility is increased.

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Introduction

A persistent problem in clinical dentistry is related to fractures occurring in vital or pulp less teeth [1,2].

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While vertical fractures in vital teeth have been observed to occur only in posterior teeth, fractures in endodontically treated teeth are observed posteriorly and anteriorly [3-6]. Even if some of these fractures could be related to concentration of forces associated with restoration with posts [7,8], fatigue loading must be considered as additional cause of root fracture [1]. Some studies have indicated that static fracture strength of an endodontically treated intact anterior tooth is not affected or even decreases with post placement [9] while failures have been related to fatigue more than maximal loading [10]. The masticatory loads may fluctuate in phase or out of phase and the overall fatigue life is inevitably dictated by the complex phase relations between the principal stress-strain vectors generated in the restored system. The fatigue failure is a multi stage process involving creation of microcracks at the interfaces, growth and coalescence of microscopic flaws into dominant cracks and stable propagation of the dominant macro cracks according to the combination of open, tear and shear modes occurring in a multiaxial stress condition. The origin of multiaxiality depends on factors such as type of external loading, geometry of structure (the stress state can be multiaxial even if the external applied load is uniaxial), residual stresses (which are multiaxial by nature) and not homogeneous material distribution.

Posts made in unidirectional reinforced composite have the mechanical behavior of a beam [27, 28] which rigidity is given by a combination of shape (diameter) and type of reinforcement (glass or carbon). Even if they have been often described to not reinforce the tooth [29], its role to maintain the core reconstitution material by unifying it with the root is particularly true for posterior teeth where masticatory functions are essentially compressive [30]. However, when loaded transversely, as is the case of an incisor, flexural behavior of the post systems should be carefully considered [31]. An incisor tooth behaves mechanically like an elastic beam during function, or more precisely, like a beam fixed at one end, as is a cantilever when not loaded along its longitudinal axis. In such failure scenario, post and core flexural and torsional characteristics should receive more research interest [11-13].

Post restorations are then complex systems where the stress distribution within the structure is multiaxial, non-uniform and depending on the magnitude and direction of the applied external loads [14]. Photoelastic analysis [15] and strain gauge tests [16,17] provided evidence of complex deformation behaviors even in presence of small applied loads. Previous investigations [17,18] have also shown that load transfer from post to root dentine structure differs according to the different cements used, confirming the occurrence of stress redistribution through the entire root and its role in lighten specific regions from high stress concentrations, especially at post-dentin interface. Nevertheless, direct experimental measurements of the stress distribution at these locations have not been found in literature. However, a theoretical well known method for calculating stress distribution within complex structures is the finite element (FE) method which allows the investigator to evaluate the influence of model parameter variation once the basic model have been correctly defined. Previous investigators have used two-dimensional axisymmetric models to describe post and core restorations mechanical behavior [19-22]. Such authors identified regions of stress concentrations that could have higher fracture potential and the relevance of some geometrical parameters in post restoration design. The validity of such analyses has been experimentally established by comparing the results of simulations with those of laboratory tests or clinical fracture mode observations either when simple models and surface strain [23] or internal failure inducing stress distributions [24] were analyzed. For the latter cases, the calculated stresses relate to fracture probability at critical stress values identifying the necessity of the correct choice of the failure criterion. The analysis of normal as well shear stresses have, in fact, shown little failure predictive potential [19] while more accurate predictions have been observed using maximum principal stresses or Von Mises criteria [20-22]. Fracture, however, are not always described to occur under limiting static loading conditions. Different critical restoration regions and fractures patterns are described to occur in fatigue testing on titanium and composite post and amalgam cores [25,26] while static strength testing (maximum load applied before failure) of the same systems leads to same fracture behavior. These authors reported that specimens loaded for more than 10^5 cycles showed a gap formation at the core-tooth interface. For the more rigid amalgam and titanium systems this was induced by the deformation of the core at the vestibular side moving away from the tooth while, for the composite posts, it was induced by the deformation of the dentine following the post intrusion in the tooth. The deformations at the dentine interface, where loads transfer from the post to the dentin occurs, are then described to play a relevant role in defining the mechanical reliability under fatigue loadings of post restorations using different retention systems. Our work analyses the mechanical behavior of an endodontically treated maxillary incisor restored by different post and cement materials adaptable to dentistry using a FEM analysis.

The present paper evaluates, using Von Mises criteria [20-22], restorative materials performance (types of post and cements) in a maxillary central incisor using three-dimensional FEA. For the investigation a 3D FEM model with all its anatomic and material characteristics of components (root, crown, root canal and post) is proposed for comparative evaluations under an ordinary masticatory load.

Materials and methods

A linear static structural analysis has been performed to calculate the stress distribution in the tooth root canal and luting cement interfaces under a load of 10 N. In order to compare the mechanical reliabilities of post restorations using different retention systems and cementing materials (especially under cycling loadings), the complex stress states and redistribution at the dentine interface, where loads transfer from the post to the dentin occurs, have been analyzed by proper choice of failure criterion.

The choice of the pertinent stress representation criterion was based on the evaluation of failure predictive potential of the analysis performed. Von Mises (equivalent stresses) energetic criterion has been then chosen as more representative of a multiaxial stress state. Under fatigue loading, in fact, the calculated stresses should relate to fracture probability and, therefore, to the assumption that different stress states having the same effect are equivalent when determining the system failure at critical stress values (failure criterion). In such cases, accurate predictions have been observed [20-22].

Solid and FE models preparation

The solid model was generated using literature data [32] for the dentine, enamel and internal volumes morphologies, while the external shape of the incisor was obtained by laser based 3D digitiser (Cyberware) of a plaster cast (Thanaka manufacturer Japan 1978). The scanned profiles were assembled in a three-dimensional wire frame structure using a 3D CAD (Autocad 12, Autodesk, Inc.) and exported into a 3D parametric solid modeler (Pro-Engineering 16.0 Parametric Technologies, USA). The tooth volumes were generated by fitting of the horizontal and vertical profiles. The geometries and volumes for the cement layer and post were also generated at this stage.

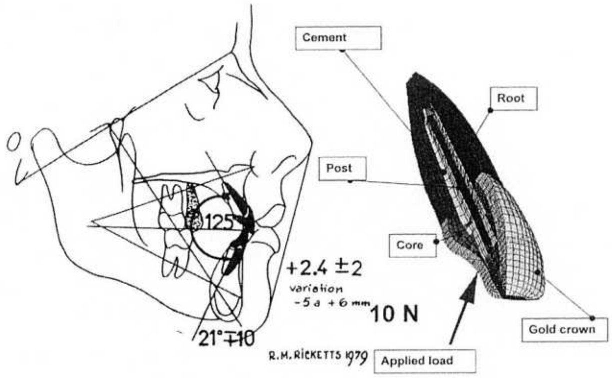

Figure 1 FEM model and loading conditions of a post restored maxillary incisor.

The FEM model was obtained by importing the solid model into ANSYS rel. 5.3 FEM software (Ansys, Inc. Houston) using IGES format. The volumes were redefined in the new environment and meshed with eight nodes brick with three degree of freedom per node, finally resulting in a model with 13,272 elements and 15,152 nodes (section in Fig. 1). Accuracy of the model has been checked by convergence tests. Particular attention has been devoted in the refinement of the mesh resulting from the convergence tests at the cement layer interfaces. Different material properties were coupled with the elements and geometries according to the volume material defined in Fig. 1 (gold crown, dentine root, core, cement and post). The carbon and glass fiber posts were considered made by long fibers (carbon or glass fiber) embedded into a polymeric matrix. These composite materials are considered orthotropic, so that they show different mechanical properties along the fiber direction (x direction) and along the other two normal directions (y and z direction). The elastic properties of the isotropic materials [36] are reported in Table 1. The carbon and glass posts mechanical characteristics [36-38] are reported in Table 2. E_x, E_y, E_z represent the elastic moduli along the three directions while ν_{xy}, ν_{xz}, ν_{yz} and G_{xy}, G_{xz}, G_{yz} are, respectively, the Poisson's ratios and the shear moduli in the orthogonal planes (xy, xz and yz).

Due to the comparative aim of the structural evaluations, the given arbitrary commercially available post geometry has been used:

- 6% conicity,
- tip diameter 1.0 mm,
- 10 mm insertion depth (about 2/3 of the root length).

Table 1 The elastic properties of the isotropic materials [36-38].

Material/component	Elastic modulus (GPa)	Poisson ratio
Gold crown	70	0.30
Dentin	18.6	0.32
Core (resin composite Biscore, Bisco USA)	12.0	0.33
Zinc-oxide phosphate (Dentspy-De Trey, Germany)	22.0	0.35
Adhesive cement resin (low modulus) (C&B, Bisco, USA)	7.0	0.28
Adhesive cement resin (high modulus) (Panavia, Kuraray, Japan)	18.6	0.28
Steel post	210	0.30

A chewing static force of 10 N was applied at 125° angle with the tooth longitudinal axis at the palatal surface of the crown as indicated in Fig. 1.

All nodes on the external surface of the root from 1/3 to root apex were constrained in all directions.

The following assumption have been made:

- complete bonding between post and cement was considered,
- dentine was assumed elastic isotropic material according to Darendelier [33] and Versluis [34],
- rigid constrains have been considered at root level.

Results and discussion

Attention was firstly directed to the comparison of the model results with existing literature clinical and in vitro experimental observations. Fig. 2 shows the differences between the stress redistribution in a tooth restored with a steel post (left hand) cemented with zinc oxide phosphate (22 GPa) and with a carbon post cemented with a softer than (7.0 GPa) and similar to dentine (18.6 GPa) cements (respectively, middle and right hand in Fig. 2) when a buccal load of 10 N (see Fig. 1) is applied. In all cases, maximum equivalent stress occurs at the vestibular side of the cement layer (interface between post and cement), which is consistent with experimentally validated 2D FEA. Stress distribution at the model midplane along the post-cement interface in the case of steel, carbon and glass posts (cemented with dentine like cements) are reported in Fig. 3. Distances in Fig. 3 are measured, as shown in the upper right side of the same figure, from the apex of the post to its coronal region (crown) along the longitudinal axis at the model midplane. In both cases, the stress uniformly increases from apex to its maximum value located between 1/2 and 2/3 of the root insertion, progressively from carbon to steel posts, and than it decreases. As reported in Fig. 2, the equivalent stress reaches maximum value of 7.5 MPa for the steel post and 3.6 and 5.4 MPa for the carbon posts cemented with softer than and dentine like cements, respectively. However, even if significantly different load transfer characteristics from post to root occur in the three cases examined, no differences are evident at level of external root structure either for stress distribution and intensities (stress is uniformly distributed and reaches a value of about 3 MPa). These observations are qualitatively in agreement with the experimental literature using external strain gauge measurements [23-35]. In particular, the investigation on

Table 2 The elastic properties of the orthotropic materials [36-38].

Property	Carbon post	Glass post
E_x (GPa)	118	37
E_y (GPa)	7.20	9.5
E_z (GPa)	7.20	9.5
ν_{xy}	0.27	0.27
ν_{xz}	0.34	0.34
ν_{yz}	0.27	0.27
G_{xy}	2.80	3.10
G_{xz}	2.70	3.50
G_{yz}	2.80	3.10

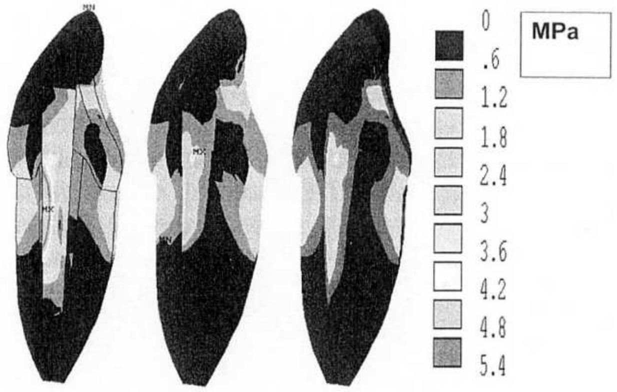

Figure 2 Von Mises equivalent stress comparison between steel and carbon posts cemented with hard (center) and soft (right) luting cements.

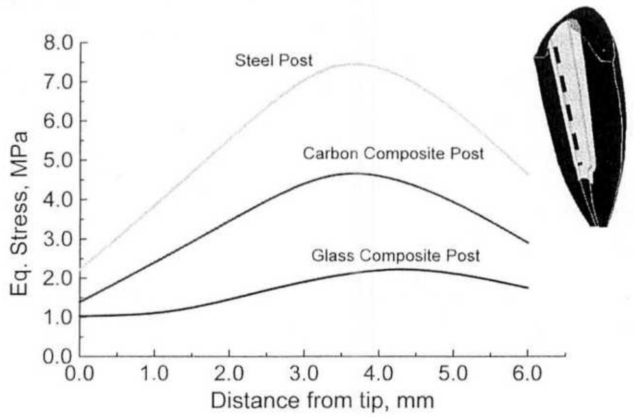

Figure 3 Von Mises equivalent stress distribution along the root canal maximum stress area (dotted line) for steel (upper curve), carbon (middle curve) and glass lower curve) composite posts.

central incisor teeth [35] showed differences in load transfer capability of cast post when different cements where used. Although details on elastic properties of the different luting materials were not reported and, hence comparative local stresses were not evaluated, it was clearly stated that the use of a cement resulted in an even distribution of stress throughout the entire external root surface and that no differences in strain gauge measurements were found between the different cementation media.

A still more favorable stress distribution has been observed in the case of restoration using more flexible glass post. The stress differences between the steel and glass restored tooth are reported in Fig. 4. As discussed before, the stress reaches a maximum value of 7.5 MPa for the steel post while it reaches a significantly lower value of 2.2 MPa for either glass posts cemented with softer than and dentine like cements. Therefore, there was not a significant difference in the stress distribution at dentin interfaces for the glass post restored tooth cemented with materials of different rigidity (Fig. 4). This observation leads to the conclusion that the more flexible the posts are, the less the rigidity of the cementing medium is relevant. Moreover, although the stress generated at the post-cement interfaces in both restoration design (Figs. 2 and 4) were significantly different for systems restored with different post and cement type, neither absolute values reached material (dentine, cement or post) failure limits [36].

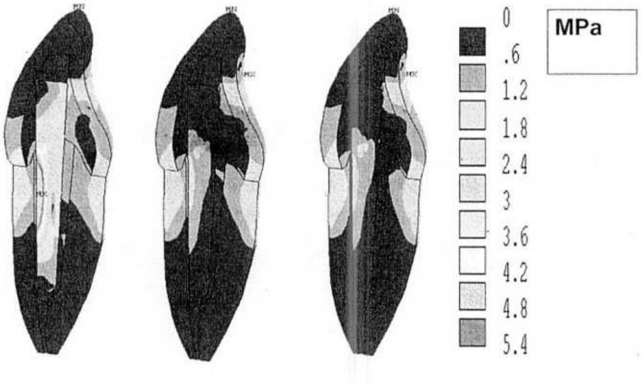

Figure 4 Von Mises equivalent stress comparison between steel and glass reinforced posts cemented with hard (center) and soft (right) luting cements.

Conclusion

The placement of an endodontic post creates an unnatural restored structure since it fills the root canal space with a material that has a defined stiffness unlike the pulp. Hence it is not possible to recreate the original stress distribution of the tooth. Steel posts are the most dangerous for the root, potentially leading to its fracture. Even working on the cement layer stress absorbing capability by using less rigid cements is not possible improve the stress arising in the system because of the high rigidity of the steel post. In a carbon post reconstruction, the elastic modulus of the cement layer strongly influences the stress absorbing capability of the system. The glass reconstruction system gives the most benign stressing condition; in this case the cement layer rigidity is less relevant compared to the carbon post configuration. Clinically both carbon and glass posts are subjected to debonding/loosening phenomena that could easily occurs in system restored with more rigid cements, toughened cement systems could improve the restoration reliability by opposing to mechanical progression of failure and crack growth. Carbon and glass posts debonding does not cause damage to tooth tissues.

Static loading at intensities of the masticatory forces, then, has been shown to be of the order of 2-8 MPa, which are well below the system critical failure stress levels. Masticatory function cycling load, however, could more easily favor crack growth and propagation in restored teeth characterized by higher levels of localized stresses at the critical interfaces such those between dentine and luting cement. Spontaneous fatigue root fractures have also be observed to occur even in non-endodontically treated teeth when subjected to heavy repetitive masticatory loads. Different failures behaviors, in fact, have been experimentally observed to occur on differently post restored teeth [37]. The results of our study confirm the importance of the rigidity of post and luting cement in the assessment of the reliability of endodontically post restored through the ability of the material to redistribute the stresses at the interface between dentine and post. Moreover, it has also been observed that the effect of the cement layer rigidity becomes irrelevant when the stiffness is lowered.

The ideal root canal post must be sufficiently elastic to accompany the natural flexural movements of the structure of the tooth, something that a very rigid metal post cannot do [38,39]. A post with biomechanical properties to those of dentin could be advantageous by reducing the risk of root fractures of teeth. A very stiff post working against the natural function of the tooth creates zones of tension and shear both in the dentine and at the interfaces of the luting cement and the post. These tensions, which intensity depends on the differences between the relative rigidities of the external root and cemented post, can cause cracks or fractures both in the tooth and core reconstitution [25,26]. For this reason we presume that clinically observed failures were principally due to crack propagation under occurs fatigue loading: the stress distribution. Glass and carbon posts exhibit high fatigue and tensile strength, and they have a Young's modulus comparable to dentin [37]. Moreover, these posts are compatible with Bis-GMA resin used in bonding procedures and so they can be bonded in root canal with adhesive resin cement and bonding systems' new generation. These bonding agents transmit stress between the post and the root structure, reducing stress concentration and preventing fracture [37,38]. Bonding between the post and the cement and between the cement and the dentin appears an important parameter to achieve optimal behavior of endodontical restorations [20].

On the contrary steel post and traditional cements, being no adhesive and also more rigid than glass and carbon posts and adhesive resin cements, do not allow a homogeneous stress distribution.

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