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Stress Prediction in a Central Incisor with Intra-radicular Restorations

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A 2D finite element analysis was applied to calculate shear and *von Mises* equivalent stresses developed, under masticatory loading, in an upper central incisor restored with cast gold post and carbon fiber reinforced epoxy resin post. Based on the predicted shear stress levels, it is concluded that the gold post model is more prone to shear failure along the post-dentin interface. Whereas shear stress concentration also occurs in both models at the core-crown interface, the stress level predicted there is higher for the carbon fiber post model which would be more susceptible to crown displacement. Finally, the prediction of *von Mises* equivalent stress indicates a non-uniform distribution, with the stress preferentially concentrated in the gold post along its interface with the tooth dentin. For the carbon fiber post restored model, on the other hand, the *von Mises* stresses are more uniformly distributed achieving its maximum level in the tooth dentin.

Keywords: *cast gold post, carbon fiber post, shear stresses, von Mises equivalent stresses*

1. Introduction

Contemporary restorative dentistry has the main purpose of rehabilitating the function and esthetic of teeth which had their structure severely degraded due to caries or fracture. Restoration of endodontically treated teeth, with large portion of their coronal dentin already damaged, is commonly achieved by installing a post in the root cavity in order to provide a base for continuing the reconstruction process and to secure the retention of the restored tooth structure. Intra-radicular posts have been used in restoration of teeth for decades, historically, with the main objective of increasing their strength, to protect them from root fractures[1-4]. However, some investigations have demonstrated that root post transmits masticatory loads to the tooth root and supporting structures[5-9]. Accordingly, research works related to the biomechanics of dental materials have been carried out to evaluate the effect of masticatory loads on the stress distribution within endodontically treated teeth restored with intra-radicular posts[10-19]. This allows one to pinpoint highly stressed regions where fracture is expected to initiate. The structural integrity and clinical longevity of post-and-core restored teeth are therefore strongly dependent on the state of stress created in their different regions due to occlusal loads. In addition to the magnitude and direction of such loads, the stress state at a given point within a restored tooth is also influenced by factors like the design and material of the post and the quantity and quality of the remaining root tissue[20-26]. According to some authors[22], as the extensive loss of root dentin increases the risk of radicular fracture, appropriate mechanical behavior of the post is considered, in this case, to be fundamental to the success of rehabilitating restored teeth.

Numerous methods are available for post-and-core build-up, but the most widely used can be classified into two basic types, namely direct and indirect techniques. The direct technique involves the use of a commercial prefabricated post adapted into the root canal which is then filled with composite resin. This technique offers the advantage of requiring only one preparatory session, thus reducing clinical procedure expenditure. Fiberglass and carbon fiber reinforced epoxy are the post materials most utilized for this type of restoration. The indirect technique, on the other hand, requires a pattern taken from the prepared root cavity to fabricate a cast post which conforms to the morphology of the prepared root canal. Cast posts are usually made of metallic alloys and are frequently indicated for teeth which, following endodontic treatment, end up with little remaining structure and/or large canal space. More recently, a technique for preparing ceramic posts has been developed[27-29] with the purpose of conferring good esthetic features and securing perfect fitting in the root canal.

The finite element method (FEM) has been used for stress and strain analysis in dental biomechanics for nearly four decades[2-6,9-12,30,31]. The subdivision of the structure allows one to determine the stress distribution and hence to identify highly stressed regions where cracks are most likely to nucleate and, eventually, lead to partial or total fracture of the restored tooth. Despite the advantages of the finite element method, it should be emphasized that the use of improper data concerning material's properties, model geometries or boundary conditions would result in deficient or even incorrect outputs[16].

The present study has the purpose of applying two-dimensional (2D) finite element method to determine the stress distribution in a maxillary central incisor, with a small root-dentin thickness, restored with two different posts, namely a cast gold post (indirect technique) and a prefabricated carbon fiber post (direct technique). One should, though, point out that two-dimensional softwares assume that the

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model's geometry remains unchanged in all sections parallel to the plane of the model. Axisymmetric models are therefore more representative and three-dimensional (3D) models would represent the most faithful simulation of clinical situations[10,16]. Three-dimensional models are surely more accurate in describing the actual state of stress but, at the same time, much more complicated to realize and they do require a much extensive computing time to be resolved[4].

Finite element results reported by Ho et al.[6] on a maxillary central incisor with and without post restoration indicated that, despite the simplifications of the 2D models, the locations of the peak dentinal stresses in the two- and three-dimensional models were similar. In addition, the 3D models demonstrated that these peak stresses, generated in the tooth due to masticatory or traumatic loading, were reduced by an average of about 10% as a result of using gold or stainless steel restoration posts. However, these reductions were slightly greater than those predicted by two-dimensional and axisymmetric models, which amounted to an average of approximately 5%[2]. This comparison seems to indicate that two-dimensional models are more conservative than their three-dimensional counterparts.

Results obtained by Meira et al.[10] have indicated that the axisymmetric model presents stress vectors with similar orientation but lower in magnitude than those detected by 2D analysis for elements in the vicinity of restoration post, and stress levels can therefore be overestimated by adopting 2D finite element analysis. It is worth mentioning that, despite eventual approximations due to the adoption of 2D rather than 3D analysis, the comparison between the models is considered to be valid, specifically in regard to the identification of critical regions where cracks can nucleate and eventually propagate leading to the loss of structural integrity and finally ultimate fracture of the restored tooth.

It is to be noted that, although the use of cast gold posts has been declining, the proposed comparison is considered relevant, taking into account the fact that many people are walking around with gold post restored teeth.

2. Methods and Models

As mentioned earlier, 2D analysis was adopted in the present study in virtue of its simplicity and low computational cost. Accordingly, two-dimensional models of a maxillary central incisor, 21 mm in length, were created by the software AutoCAD 2000 making use of data from Wheeler[32]. These models are presented in Figures 1 and 2 in a vestibular-lingual cross section and both of them include the supporting structures, namely periodontal ligament (0.175 mm), cortical bone (0.5 mm) and sponge bone. The cement layer that surrounds the root is considered to have the same elastic properties as those of the tooth dentin (and hence cement and dentin in this study are admitted to be one and the same material). The average thickness of the root dentin was taken as 1 mm, thus simulating a weakened root, frequently encountered in real clinical cases.

The model presented in Figure 1, denominated Model 1, represents a pulpless tooth, with 4 mm of remaining gutta-percha apical seal, restored with a cast gold post. Figure 2 presents the second model (Model 2), representing the same tooth structure described above, but now with a prefabricated cylindrical carbon fiber post, 12 mm long and 1.8 mm wide, centered in the root cavity which is filled with composite resin. A common feature of the two models refers to the fact that a ceramic crown is placed in the coronal portion of both models.

All materials used in the simulation, including the carbon fiber post, were assumed to be homogeneous, isotropic and linear elastic and their elastic properties (elastic modulus and Poisson's ratio) are presented in Table 1. Although the carbon fiber post has different

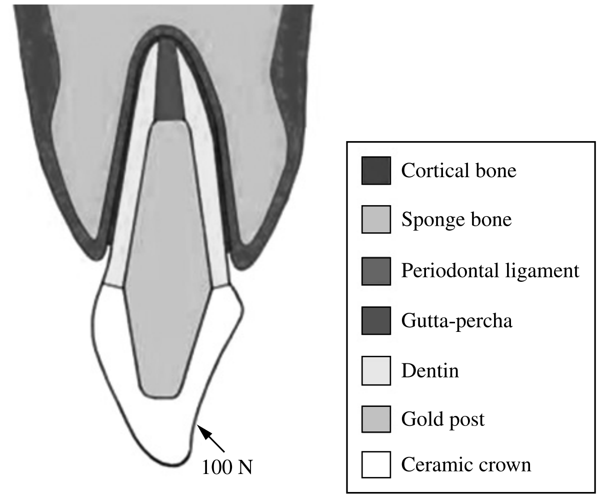

Figure 1. Tooth model restored with cast gold post.

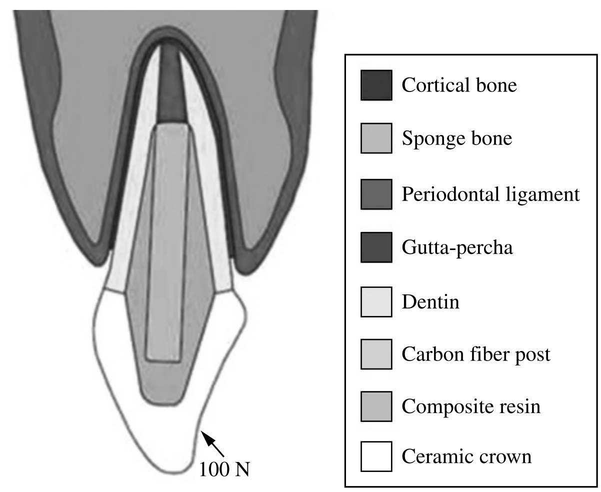

Figure 2. Tooth model restored with carbon fiber post.

Table 1. Elastic properties of the materials involved in the FEM calculation[2].

Material	Elastic modulus (MPa)	Poisson's ratio
Dentin	18.6×10^3	0.31
Periodontal ligament	69	0.45
Cortical bone	13.7×10^3	0.30
Sponge bone	1.37×10^3	0.30
Gutta-percha	0.69	0.45
Gold post	99.3×10^3	0.33
Carbon fiber reinforced epoxy	25×10^3	0.31
Composite resin	22.2×10^3	0.28
Ceramic crown	96×10^3	0.26

elastic constants in the longitudinal and transverse directions, it was considered to be isotropic in order to reduce the mismatch effect in the system post-composite resin.

Model 1 and Model 2 were meshed respectively in 11,274 and 11,099 quadratic elements with 11,455 and 11,278 nodes. All nodes on the bone surface below the apex were constrained to avoid their movement in the X (horizontal) and Y (vertical) directions. In order to simulate masticatory loading, a 100 N force was considered to be uniformly distributed along an 8 mm span and oriented diagonally at an angle of 45° with respect to the longitudinal axis of the tooth, as indicated in Figures 1 and 2.

Applying the finite element method to the meshed models for the given boundary and loading conditions, the stress distribution can be evaluated and a comparison between the two models can be visualized.

3. Results

The results obtained with the finite element method are presented in terms of the maximum in-plane shear stress and *von Mises* equivalent stress, developed in the different regions of the two models in question. Considering Model 1, the shear stress distribution and the *von Mises* equivalent stresses are presented in Figures 3 and 4, respectively. For Model 2, Figure 5 is representative of the shear stress distribution, while Figure 6 is indicative of the *von Mises* equivalent stresses.

The importance of evaluating shear stresses in dentistry is mainly related to the fact that excessively high stress levels may lead to loss of adhesion at the interface of different materials with the consequent loss of structural integrity and eventually fracture of the restored tooth. The *von Mises* equivalent stress combines normal and shear stresses, acting at a given point, in a resultant normal stress, which, on achieving high levels can cause fracture due to the brittle nature of tooth tissues.

As can be observed from Figure 3, the gold post restored incisor presented, under occlusal loading, shear stress concentration at the upper end of the intra-radicular post close to the endodontic gutta-percha filling, where a magnitude of 6 MPa was achieved. One may also observe regions of concentrated shear stress of the same magnitude at points, near the post apex, in the interface between the post and the radicular dentin, on both the lingual and vestibular sides of the tooth. The highest level of shear stress, though, was found to be present at the point of load application, where a maximum value of about 13.4 MPa was achieved.

In regard to the *von Mises* equivalent stress, Figure 4 indicates a non-uniform distribution, with the stress preferentially concentrated in the intra-radicular gold post along its interface with the tooth dentin, achieving a maximum level of about 18 MPa. Stress concentrations can also be observed in the dentin at the upper extremity and on both sides of the gold post, particularly the vestibular side. At the point of load application, the von Mises equivalent stress achieved its maximum level of approximately 45.8 MPa.

As to the carbon fiber post (Model 2), Figure 5 indicates the presence of small regions of shear stress concentration in the apical part of the tooth root. One such region is seen to be present in the dentin close to the periodontal ligament on the lingual side of the tooth, where a shear stress level of about 3 MPa is reached. Another such region can also be observed at the upper end of the intra-radicular post. Higher shear stress levels (6 MPa) are detected, as can be seen from the figure, in the middle of the post, close to the cervical region of the tooth as well as at the post apical (upper) extremity. In the coronary region of the tooth, shear stresses are found to be still higher, especially in the ceramic crown at the resin nucleous. The maximum shear stress detected there corresponds to the point of load application and amounts to approximately 11 MPa.

The prediction via FEM of the *von Mises* equivalent stress developed in the carbon fiber post restored tooth has indicated, as shown in Figure 6, that stress levels of the order of 9 MPa are achieved in the radicular dentin. However, as can be seen from this figure, the equivalent stress exhibits higher levels (12 MPa) on the vestibular side, opposite to the side where the load is applied to the tooth, particularly in the cervical region at the periodontal ligament. A maximum *von Mises* equivalent stress level of about 53 MPa occurs at the point where the load is applied and a region of equivalent stress concentration extends from this point to the area around the coronary extremity of the resin nucleous.

4. Discussion

The ability of the intra-radicular post, placed in substitution of lost tooth tissue, to support coronal restoration under occlusal loads is a critical factor for the success of this type of dental treatment. This is borne out by the fact that failure of the post leads, almost invariably, to failure of the coronal restoration.

The FEM can play an important role in predicting the state of stress acting in the different regions of the restored tooth under

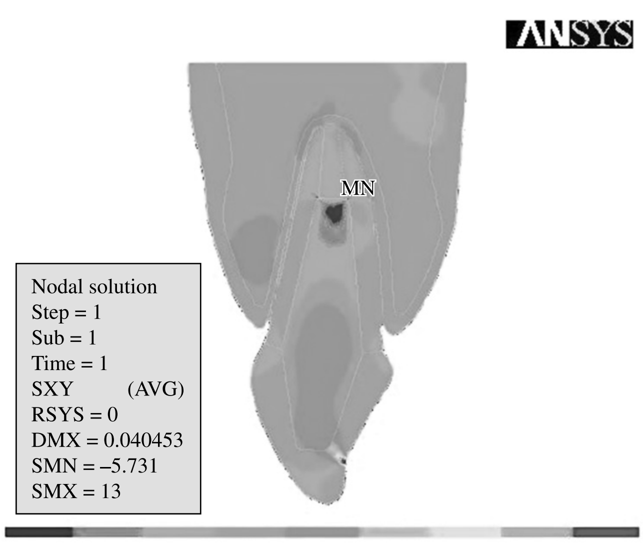

Figure 3. Shear stress (MPa) distribution in Model 1.

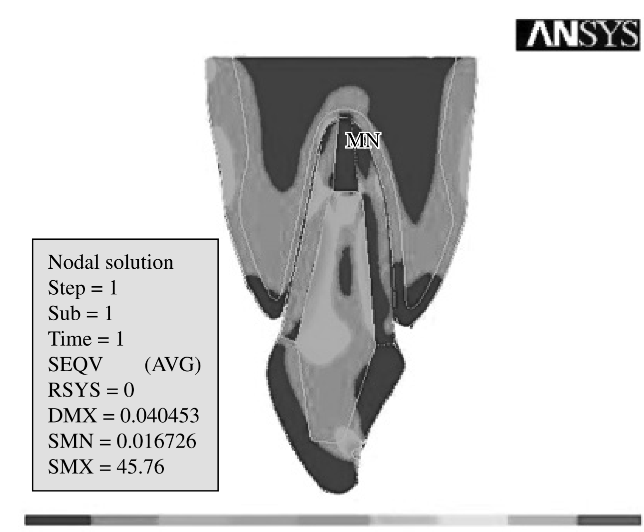

Figure 4. *Von Mises* equivalent stresses (MPa) in Model 1.

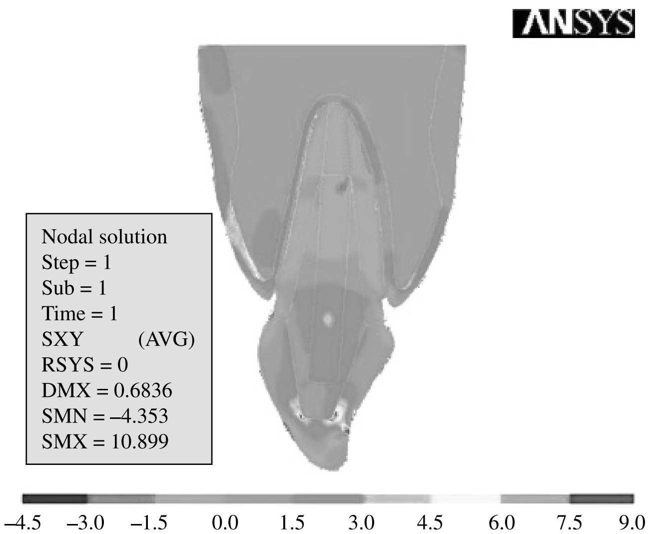

Figure 5. Shear stress (MPa) distribution in Model 2.

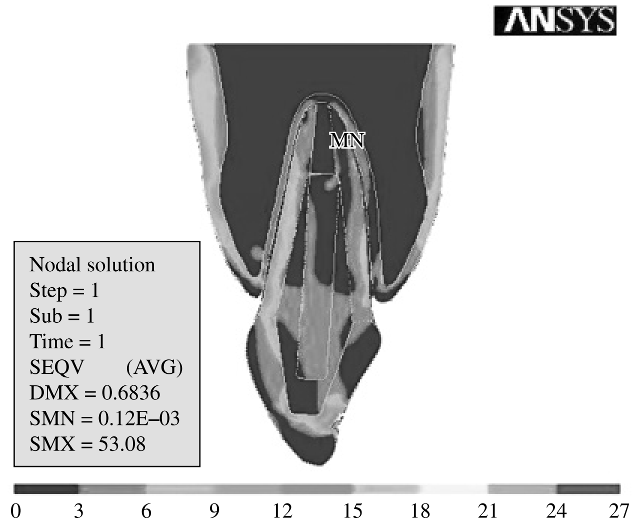

Figure 6. *Von Mises* equivalent stresses (MPa) in Model 2.

masticatory loads. This, in turn, serves as a pertinent tool to pinpoint regions within the restored structure that are susceptible to fracture initiation and crack propagation, meaning failure of the restoration process. However, the success of applying the FEM requires appropriate choice of the models which have to be compatible with the boundary and loading conditions imposed on the structure. The structures modeled in this study can vary from one individual to another and the shear stress evaluation was carried out under static type loading. This imposes a limitation on the general applicability of the results despite their meaningful significance both qualitatively and quantitatively.

In regard to the FEA developed in the present study, two considerations should be made. The first one is related to the fact that the stress calculation has been carried out based on a two dimensional simulation which has been proven, by previous publications, to be sufficiently adequate to real situations[2,4,6,19,26,33-36]. The second consideration refers to the assumption that the carbon fiber post has an isotropic elastic behavior while, in fact, it is well known that unidirectionally oriented fiber composites are orthotropic, with the transverse modulus representing a small fraction of the longitudinal modulus. Such a difference in the elastic moduli would lead to a more pronounced mismatch effect in the system post-composite resin. Hence, the use of only one elastic modulus for the carbon fiber post (25 GPa), which is close to that of the composite resin (22.2 GPa), was considered more suitable to the simulation in order to reduce the mismatch effect. In reality, isotropic carbon fiber posts could be fabricated by randomly orienting short carbon fibers in the epoxy resin matrix, whereby the desired value of the modulus of elasticity can be obtained by adjusting the fiber volume fraction.

The results of the present study have revealed the existence, under masticatory loads, of small regions of shear stress concentration at the interface between the gold post and the dentin. One should therefore consider the possibility of failure by displacement along this interface. For the carbon fiber post restored model, on the other hand, a shear stress level of about 3 MPa is developed in the dentin close to the periodontal tooth ligament, as shown in Figure 5. This stress level amounts to only 50% of that observed at the gold post-dentin interface. Although one may not fully discard the possibility of shear failure through the dentin, it is possible to conclude that Model 1 is more prone to this type of failure, in comparison to Model 2.

Far from interfaces, the FEM results presented in Figures 3 and 5 demonstrate that the shear stress in both models is concentrated also in the posts, suggesting that failure can take place by shearing of the post if its fracture resistance is achieved. According to the literature[5,28,37-39], the stability of the post is related to its geometry. Conic or short posts, which did not achieve appropriate penetration into the root canal, have more probability of being extruded.

Shear stress concentrations were also found to be present at core-crown interfaces, predisposing the structure to displacement of the crown during mastication. Adequate preparation of the core together with the use of adhesive cementation can therefore contribute to minimizing the risk of such displacement. However, this type of cementation is not adequate for metal posts, which represents a disadvantage of choosing such posts for restorative treatment. At this point, it is worth mentioning that stress levels encountered by FEM at the core-crown interfaces are higher for Model 2 compared to Model 1 (Figures 3 and 5).

Considering the results of the *von Mises* equivalent stress calculations (Figures 4 and 6), one can conclude that the use of carbon fiber post, which is less rigid than cast gold, results in a more uniform stress distribution in comparison with that associated with the more rigid gold post. One can also conclude that the maximum *von Mises* stress level achieved in the gold is almost 100% higher than that developed in the carbon fiber post. The maximum *von Mises* stress acting in the dentin, on the other hand, is seen to be a little higher in Model 2 as compared to Model 1. These conclusions seem to be in qualitative agreement with the results reported by Santos et al.[3] on the distribution of the first principal stress in metallic cast post and fiber glass models, both in the bonded condition.

Figures 4 and 6 indicate that *von Mises* equivalent stress in both models is concentrated in the cervical region as well as in the area around the coronary extremity of the resin nucleous. According to some authors[22,40], the cervical third is the region which has more propensity to fracture in intra-radicular post restored teeth, particularly in those with reduced periodontal support. High *von Mises* equivalent stress levels encountered at the apical end of the posts in both models seem to suggest that the geometry of the post in this extremity can contribute to the stress state acting there. Accordingly, acute angles should be avoided to prevent crack initiation and, consequently, radicular fracture. Further, in agreement with an observation made by Sadegui[18], the present study showed that the palatine side is submitted to higher normal stress levels, indicating that one may opt, during root preparation, for more wearing on the vestibular side.

Finally, it must be emphasized that failure in treatments involving post-and-core restorations are related to masticatory loads, restoration geometry and restoration materials. Occasionally, though, radicular fracture can occur even in well executed dental restorations. This is believed to be, essentially, related to lack of precise information regarding the forces that act on restored teeth during mastication. Precise definition of these forces followed by appropriate applications of the finite element method to predict the stress state at critical points within a restored tooth seems to be the path followed by research workers in the field of dental biomechanics.

5. Conclusions

The stress distribution in a restored maxillary central incisor was evaluated by means of 2D finite element analysis. Two different models were considered adopting a cast gold post and a carbon fiber reinforced epoxy post. Based on the results obtained from the numerical simulations, the following conclusions can be drawn:

- Whereas shear stress concentration in the gold post restored tooth (Model 1) occurs at the post-dentin interface, regions of high level shear stress are found to be present within the radicular dentin of the carbon fiber post restored model (Model 2).
- Based on the predicted shear stress levels in both models, one can conclude that the gold restored tooth is more prone to shear failure than that restored by the prefabricated carbon fiber post.
- Shear stress concentration occurs in both models also at the core-crown interface. However, the stress levels predicted by FEM are found to be higher for Model 2 compared to Model 1. Appropriate preparation of the core with the use of adhesive cementation is thus required, particularly in the case of Model 2, so as to minimize the risk of crown displacement during mastication.
- The elastic moduli of the materials involved in the restoration process have a considerable bearing on the *von Mises* equivalent stress distribution pattern developed in the restored tooth under occlusal loading. A tendency for this stress distribution to be more uniform is observed for Model 2 as compared to Model 1, which is considered to be consistent with the fact that the carbon fiber reinforced post is less rigid than its gold counterpart.
- *Von Mises* equivalent stress concentration in Model 1 is detected in the gold post, along its interface with the tooth dentin, as well as within the dentin at the extremity and on both sides of the post. For Model 2, on the other hand, high equivalent stress levels are achieved within the radicular dentin, particularly in the cervical region at the periodontal ligament.

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