STRESS ANALYSIS OF HEALTHY AND ENDODONTICALLY TREATED CENTRAL INCISORS

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Abstract. *The purpose of this investigation was to carry out experimental as well as theoretical evaluations of the mechanical behavior of maxillary central incisors under the action of 45 – degree, static, concentrated forces. In the experiments, thirty specimens were clamped in steel rings filled with acrylic resin and tested to failure in an INSTRON machine. The applied forces and the corresponded displacements were recorded. Numerical models of this situation, based on 2-D as well as 3-D meshes, were created using the finite element code ANSYS. In addition, using the same program, another group of models was simulated. In the second group, the acrylic resin and steel rings were replaced by the maxillary bone, in order to simulate the buccal environment. The correlations involving the global apparent stiffness of the first group of numerical models and the experiments were fairly good. On the other hand, the stiffness of the second group of models, on the main, was significantly higher in comparison with the values calculated from the "in vitro" experimental results.*

Keywords: *Central incisors, Finite element simulation, Destructive evaluation.*

1. Introduction

The biomechanical functions of teeth generally result in mechanical stresses which are transferred from the occlusal surface to the outer hard and brittle enamel layer, across the dentin-enamel junction and finally into the relatively soft but tough dentin region. Since the mechanical properties of the material in each of these regions are not the same, the stress analysis problem in a tooth subjected to biting forces is not simple. The location of the incisors in the mouth, as well as the different tooth regions of a healthy upper central incisor, in particular, including the maxillary bone, are illustrated in Figure 1. Understanding the details of the stress distributions and magnitudes, the resulting strains and displacements, and their relations with the structure of the tooth and its surroundings, can provide insight into the manner in which teeth function, as well as better prognosis in clinical practice and possibly also new ideas for improving synthetic materials. Studies to obtain such important informations can be based on theoretical analysis, as well as "in vitro" experiments, or in a combination of both.

As far as the theoretical approach is concerned, the Finite Element Method (FEM) has become an important and popular numerical technique in stress analysis of engineering structures and has been applied to dental biomechanics for more than two decades Thresher and Saito (1973), Farah et al. (1973), Ho et al. (1994), Yaman et al. (1998). In particular, the FEM has become widely used for the stress analysis of biological structures subjected to mechanical loads because it can model complex geometrical shapes and materials that are not homogeneous. The FEM program ANSYS was used in the numerical analysis carried out during the course of this investigation.

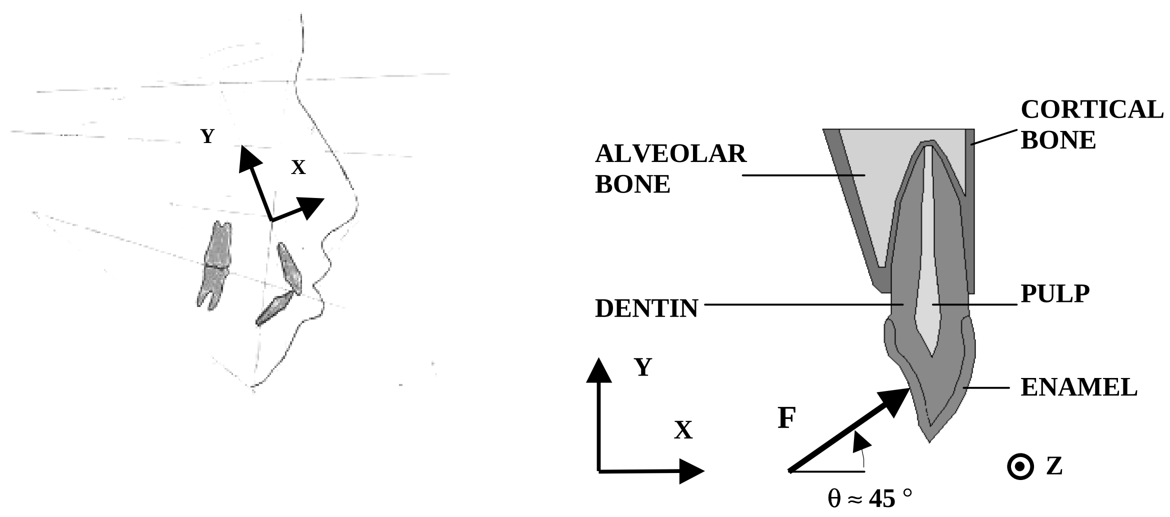

Figure 1 – Location of a central upper incisor and its main regions when clamped in the maxillary bone.

The present study analyses the stress distributions and the displacements in a maxillary central incisor subjected to a static force (F) applied in the incisal edge, about 4 mm from the tip of the crown, with an inclination (θ) of about 45 degrees relatively to the longitudinal direction of the tooth (i.e. direction Y), as shown in Figure 1. The investigation included “in vitro” experiments, using an INSTRON machine, as well as 2-D and 3-D numerical simulations based on two kinds of FEM models.

2. Materials and Methods

2.1 Experimental aspects

During the experimental phase of this work, eighteen (18) extracted upper central incisors, in average about 26 mm long, and free of cervical caries, were used. Following the recommendations presented by Dean et al. (1998), eight (8, the control group), out of these eighteen teeth, had crown preparation, but no endodontic treatment. The remaining ten (10) specimens received both endodontic treatment as well as crown preparation, and their roots, in which the total length varied from 14.5 to 16.5 mm, were restored with a Degussa-Hüls cast silver alloy (Luz, 1999; Levy Neto et al., 2001). All the eighteen specimens had their roots clamped into rings of stainless steel, which were 23 mm long and had an external diameter of 19 mm, using acrylic resin. The rings were fixed into place in a special device, as shown in Figure 2, and tested to failure using an INSTRON machine. A force F, in which the maximum magnitude was 100 N, was applied to all specimens, and the rate of vertical displacement during the tests was 0.5 mm/min.

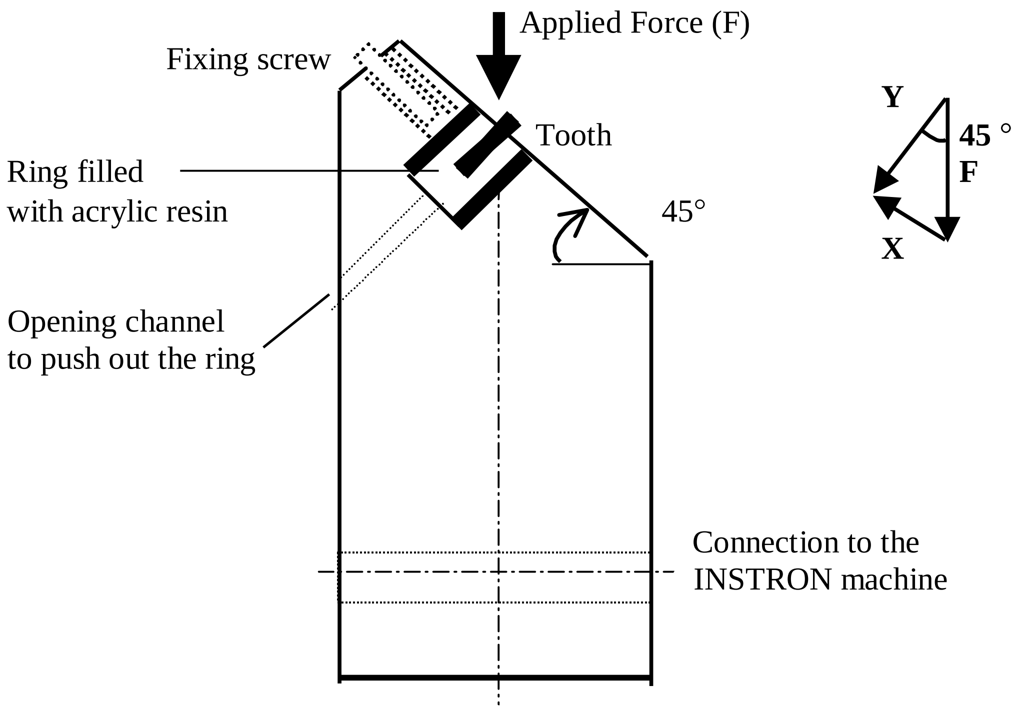

Figure 2 – Lateral view of the device developed for the destructive evaluation of the teeth.

For the eighteen teeth tested in this study, the original crown was cut out 1 mm above its base (i.e. at the root/crown junction), and the distance from the top of the reconstructed crow to its base was standardized with 10 mm. The crowns were reconstructed using the resin restorative Z-100 from 3M, which was chosen because its polymerization is rapidly activated in the presence of light. The position of all the teeth inside the steel rings was carefully examined in each case. In average, for the teeth tested in this study, the Meso-Distal as well as the Vestibular-Palatine distances of the crows were approximately 8.5 and 7.5 mm, respectively.

An additional group of twelve (12) specimens were also tested to failure in the INSTRON machine, using the same procedure described above (Brito, 2000; Brito et al., 2002). This group consisted of twelve identical, 14.9 mm long, plastic analogous of teeth roots (Viade Products Inc.), simulating endodonticaly treated maxillary central upper incisor roots, which were restored with a cast silver alloy (Silver Pratalloy Degussa-Hüls) and received crown preparation. The transparent plastic roots were subjected to a spectrometric identification, using a 1750 (FTIR) PERKIN ELMER infrared spectrophotometer, which suggested that the material is a copolymer of styrene and poly methyl methacrylate (Takahashi, M.F.K., 2002). From the total length of 14.9 mm, the plastic roots have two main regions: (i) 11.6 mm is a hollow segment and corresponds to the conduct which is prepared to accommodate the metallic restoration of cast silver, and (ii) the remaining 3.3 mm, at the end of the root, is a solid seal. In total, thirty (30) specimens were tested: (i) eight natural roots with crown preparation; (ii) ten roots endodonticaly treated and restored with cast silver, as well as with crown preparation; and (iii) twelve plastic analogous roots restored with cast silver and with crown preparation.

In order to make sure that the steel rings and the teeth were centralized with respect to each other (i.e. with their longitudinal central axis coincident), a special circular device with four adjusting screws, perpendicular to each other, as illustrated in Figure 3, was manufactured with the purpose of holding the teeth along the axis of revolution of the steel ring, during the polymerization of the acrylic resin Levy Neto et al. (2000). Then, the longitudinal direction of the teeth was always parallel to the coordinate Y. This procedure also made easier the application of the forces at the same point when each of the specimens were tested, contributing for the repeatability of the tests conditions. All specimens were subjected to a 45-degree load, relatively to the direction Y, applied monotonically at a constant rate of 0.5 mm/min, until failure occurred.

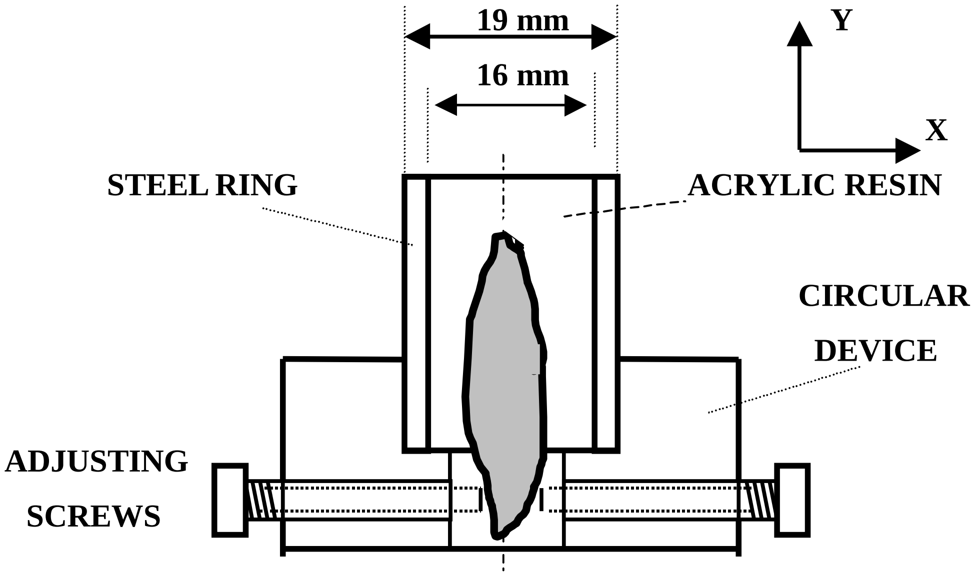

Figure 3 – Cross section of the circular device used to centralize the teeth.

2.2. Finite element modeling

2.2.1 Teeth clamped in the maxillary bone

In the initial phase of this study, a two-dimension (2D) linear analysis, assuming that the tooth is in a plane strain state, was adopted (Albuquerque et al., 1999). The element chosen for the finite element mesh was a six nodes 2D triangular element, in which the shape functions of the displacements are quadratic, allowing the stresses and the strains to vary continuously within the element (ANSYS, 1997). In the 2-D meshes, which included at least 1258 elements, each one of the regions illustrated in Figure 1 had a different set of mechanical properties (Levy Neto et al., 2001). The material inside each element was considered to be isotropic and homogeneous, and their elastic properties (Elasticity Modulus, E, and Poisson ratio, ν), according to Albuquerque et al. (1999) and Graig (1989), are shown in Table 1. The geometry of the pulp was approximated by a combination of conical and cylindrical segments.

Table 1 - Elastic properties of materials (Albuquerque et al., 1999; Graig 1989).

MATERIAL	Elasticity Modulus [GPa]	Poisson Ratio
Enamel	41.0	0.30
Dentin	18.6	0.31
Pulp	0.002	0.45
Cortical Bone	13.7	0.30
Alveolar Bone	1.37	0.30
Acrylic Resin	2.76	0.35
Silver Alloy (Degussa)	76.0	0.37

The 3-D FEM meshes, based on ten nodes tetrahedron elements, were obtained extruding the 2-D meshes, along the direction Z, by 8.5 mm. The FEM mesh shown in Figure 4 refers to the 3-D model that includes the tooth (crown and dentin) and the maxillary bone (cortical and alveolar). In the 3-D meshes, which included at least 9013 elements, the region associated with the pulp, in the case of the natural tooth, or a metallic core, in the case of a tooth treated endodonticaly, was centralized, relatively to the direction Z, and extruded by 2.6 mm. The remained volume around was completed with dentin. The mechanical properties in each region, assumed to be isotropic, were obtained from Table 1.

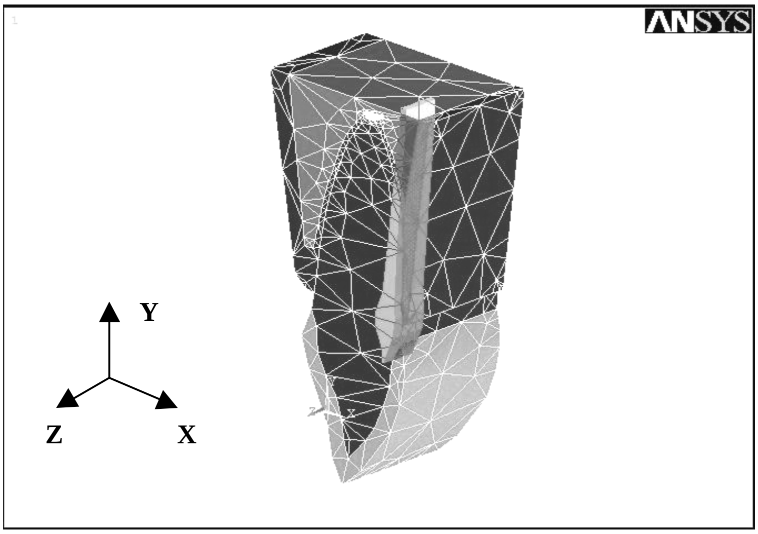

Figure 4 – FEM mesh for the central upper incisor and the maxillary bone.

In the 2-D analyses, all the nodes located along the top horizontal line where the maxillary bone ends, as shown in Figure 1, were fully clamped (i.e. all degrees of freedom restricted). In the 3-D analyses, in a similar way, all the nodes located at the (X,Z) top plane, corresponding to the end of the region of the maxillary bone, as illustrated in Figure 4, were clamped. The degrees of freedom of the remaining nodes, for the 2-D and 3-D meshes, were free.

2.2.2. Teeth clamped in acrylic resin ring

In the other FEM 2-D and 3-D meshes, corresponding to the simulation of the experiments carried out so far, the regions associated to the cortical and the alveolar bones were replaced by a single region with the geometry and the elastic properties of the cylinder of acrylic resin surrounding the tooth. The acrylic resin, as shown in Figure 3, was used to fix the tooth inside a stainless steel ring. Due to the fact that the acrylic resin is completely surrounded by the steel ring, which is about 70 times stiffer than the resin, all the degrees of freedom of the nodes located at the external surface of resin were totally restricted to simulate a boundary condition of perfect clamping.

2.2.3. Additional features of the finite element models

In all the linear elastic simulations carried out in this study, for the 2-D and the 3-D FEM meshes described in sections 2.2.1 and 2.2.2, the load assumed as occlusal force was always F = 100 N, which corresponds to the average value of the biting force in a central incisor found in the literature (Graig, 1989 and Ho et al., 1994). In the experiments as well as in the numerical simulations F was applied in the incisal edge of the teeth, about 4 mm from the tip of the crown, as shown in Figure 1. The force F always belonged to the plane (X,Y) and was inclined by 45 ° relatively to the X direction. In the 2-D meshes F was applied to a single node, whereas for the 3-D meshes it was distributed along a line of nodes in the Z direction. In both cases, the resultant of F was equal to 100 N.

The number of elements in the 2-D and 3-D meshes was increased until convergence in the numerical results was observed. In this study in particular, the maximum horizontal displacement at the tip of the teeth was adopted as reference in the convergence analysis. Overall, depending on the boundary conditions and the materials involved, twelve different types of model (6 for the 2-D and 6 for the 3-D analyses) were created using the program ANSYS.

3. Experimental and Numerical Results

3.1. Experimental Results

The failure load ($\mathbf{F_{MAX}}$), for the eight **natural roots** with crown preparation tested (i.e. the control group), varied from about 441 to 1303 N. The **average** and the standard deviation were **1031 N** and 288 N, respectively, and the coefficient of variation about **28%**. In **most** cases, the diagram relating the applied force (**F**) and the vertical displacement imposed by the INSTRON machine ($\delta_I = [(\delta_X)^2 + (\delta_Y)^2]^{1/2}$) was a straight line, from about the onset of loading to point corresponding to the maximum force (**F_{MAX}**), as shown in Figure 5.a.

In the remaining few tests involving the natural roots without endodontic treatment, instead of a single straight line, the diagrams presented two segments of straight line, with different inclinations, as illustrated in Figure 5.b. In all these initial eight testes, the behavior of the teeth was typically brittle, and the values of F_{MAX} were well above the biting force, F = 100 N, obtained from the literature (Graig, 1989 and Ho et al., 1994). The maximum displacement imposed by the INSTRON machine upon these specimens at their final failure (δ_I) varied from 0.32 to 0.86 mm. The average and the standard deviation were 0.55 mm and 0.20 mm, respectively, showing a great deal of scatter. Such displacement values, however, are very small relatively to the average dimensions of the teeth: length of 26 mm; meso-distal distance of the crown 6.5 mm; and vestibular-palatine distance of the crown 7.5 mm, indicating that the mechanical behavior of the teeth is brittle.

The behavior of the other twenty-two specimens was similar to those presented above, and only some slight differences were observed. The failure load (**F_{MAX}**), of the ten natural roots **restored with cast silver** and with crown preparation tested, varied from about 569 to 1560 N. The **average** and the standard deviation were **1090 N** and 317 N, respectively, and the coefficient of variation about **29%**. The main difference from the results presented in Figure 5.a and 5.b was in the final failure which was not as brittle as before, but rather progressive instead, as shown in Figure 6.a.

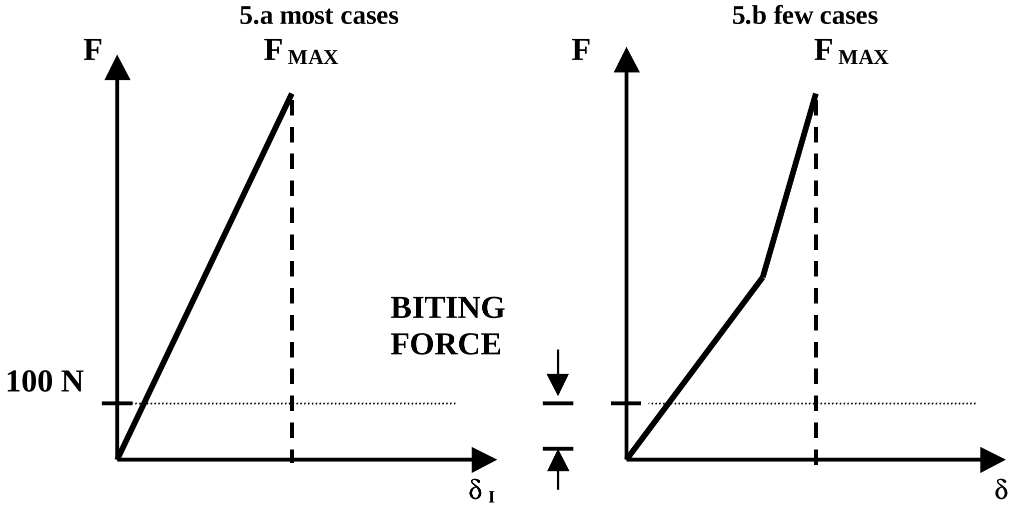

Figure 5 – Force – displacement diagrams of the test results of the eight **natural roots** with crown preparation.

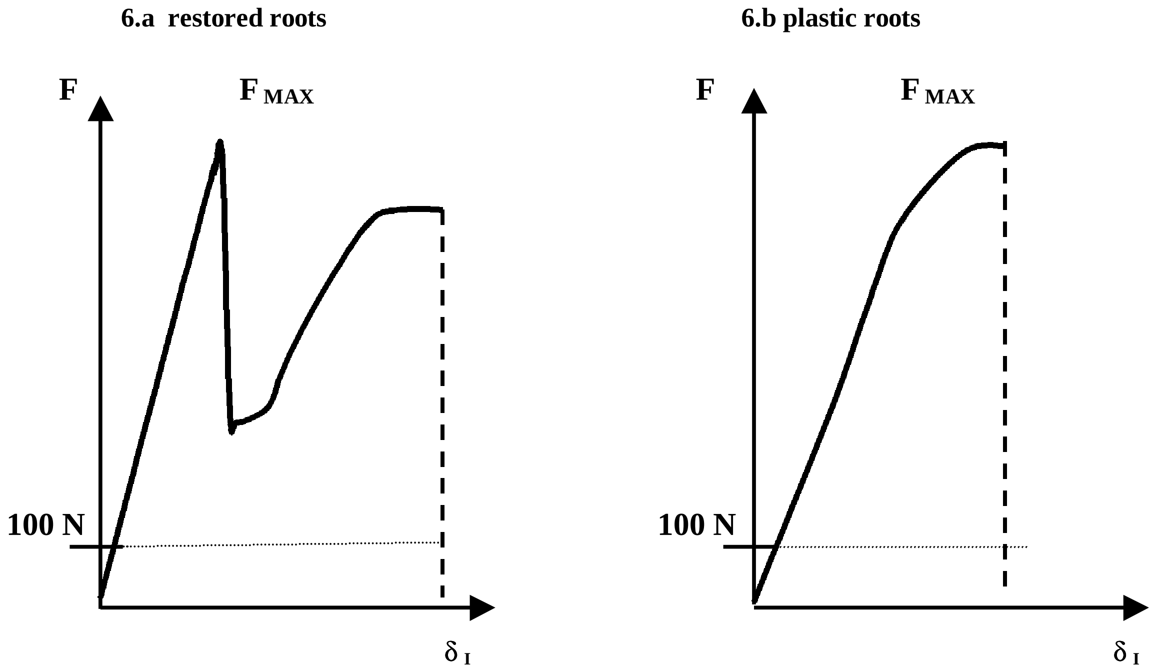

Figure 6 – Force – displacement diagrams of the test results of the ten specimens with restored **natural** roots (6.a), and the twelve specimens endowed with analogous **plastic** roots.

Finally, the failure load (**F** $_{MAX}$), of the twelve **plastic** roots **restored with cast silver** and with crown preparation tested, varied from about 726 to 1118 N. The **average** and the standard deviation were **859 N** and 129 N, respectively, and the coefficient of variation about **15%**. The main difference from the results presented in Figure 5.a and 5.b was in the final portion of the force displacement diagram which presented a nonlinear behavior previously to the final failure, as shown in Figure 6.b.

3.2. Numerical Results

3.2.1. Model Tooth – Maxillary Bone

The 2-D numerical models are rather limited and were used in this study mainly as an intermediate step towards the 3-D models. For instance, the extension of the pulp along the coordinated **Z** (as illustrated in Figures 1 and 4), corresponding to the meso-distal direction of the tooth, is only a fraction of the total width at the base of the crown. In an average male central incisor this width is about 8.5 mm, while the extension of the pulp (centralized along the direction z) is approximately 2.6 mm (Picosse, 1987). This detail was only taken into account in the 3-D analyses.

From the 2-D FEM model concerned with the natural teeth (control group) in particular, which includes the maxillary bone and uses as mastication force F = 100 N, the following results were obtained:

- Displacement δ_X (along X), varying from 0 to 0.72 . 10^{-3} mm;
- Displacement δ_Y (along Y), varying from – 0.67 . 10^{-4} to 0.15 . 10^{-3} mm;
- Normal stress along Y, σ_Y , varying from – 64.7 to 46.0 MPa; and
- Equivalent von Mises stress, σ_{vM} , varying from 0.01 to 52.50 MPa.

The distribution of the numerical values of δ_X for the control group is presented in Figure 7, indicating that δ_X increases from the from the clamped base at the maxillary bone, towards the tip of the tooth in the crown. The displacements along Y, δ_Y, and the normal stresses σ_Y , indicated that the vestibular (or labial) edge (facing the lips) is compressed ($\sigma < 0$) and that the palatine edge (facing the tongue) is subjected to tensile stresses ($\sigma > 0$) (Levy Neto et al., 2001).

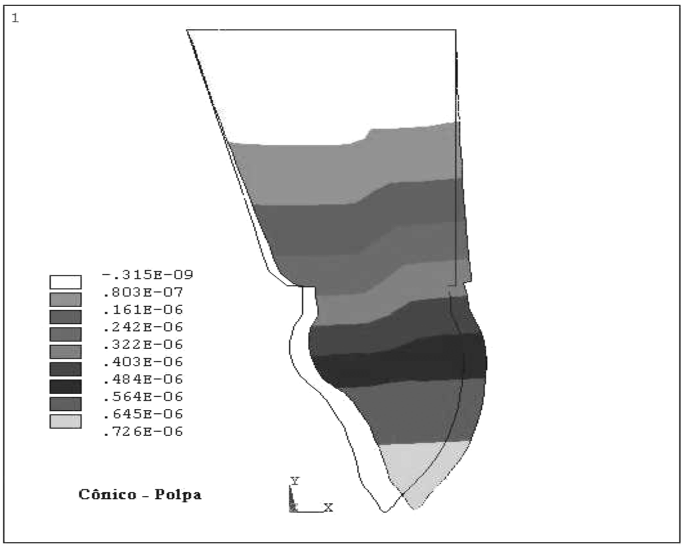

Figure 7 – Distribution of displacements along X [m] for the 2-D analysis concerned with the natural teeth.

The values of the equivalent von Mises stresses obtained from the 2-D models, σ_{vM} , suggested that the equivalent stresses are higher at the external borders, rather than in the central regions of the teeth, even for the teeth restored with metallic cores (i.e. cast silver). For the natural teeth, the stresses in the region corresponding to the pulp are significantly reduced due to the fact that elasticity modulus of the pulp is negligible in comparison to the modulus of the dentin

From the 3-D models, the maximum von Mises stresses, σ_{vM} , were obtained for each region of the specimens (i.e. dentin, enamel in the crown and maxillary bone): (i) with natural roots and crown preparation (**control group**); as well as (ii) with natural roots and restored with silver, and presented in Table 2.

Table 2 – Maximum von Mises equivalent stresses at the different regions of the 3-D mesh.

REGION	**Maximum von Mises stresses, σ_{vM} [MPa]**	
	CONTROL GROUP	RESTORED WITH SILVER
DENTIN	16.4	18.1
ENAMEL	27.1	26.6
CORTICAL BONE	38.0	38.9
ALVEOLAR BONE	8.03	9.12

3.2.2. Model Tooth – Acrylic Resin

In addition to the results presented in Figure 7 and Table 2, based on the 2-D and 3-D FEM models, respectively, and concerned with the buccal environment, another numerical simulation in which the maxillary bone was replaced by a cylinder of acrylic resin, and corresponding to the "in vitro" experiments, was carried out. The occlusal force used in this new model, F = 100 N, was same as in the previous FEM models. In particular, due to the fact that the elasticity modulus of the acrylic resin, E = 2.76 GPa, is significantly lower than the elasticity modulus of the cortical bone, E = 13.7 GPa, as presented in Table 1, the displacements obtained from these additional simulations, which are concerned with the "in vitro" tests illustrated in Figure 2, were much higher. Since the assumed mastication force, F = 100 N, was the same in both models, the global apparent stiffness of the system, K (ratio of F = 100 N divided by the total displacement at the point of application of F, given by equation 1), was reduced when the bone was replaced by the resin. In the simulations concerned with the specimens which incorporated the analogous plastic roots, it was assumed that the elasticity modulus of the styrene and poly methyl methacrylate copolymer was E = 5 GPa in the first simulation and E = 10 GPa in the second.

$$\boldsymbol{K} = \frac{\boldsymbol{F}}{\sqrt{\delta_x^2 + \delta_y^2}} \qquad (1)$$

where:

F is the force of 100N, applied with an inclination of 45°, 4mm below of the tip of the crown, as shown in Figure 1;
δ_x is the deflection at the point of application of F, along the direction x, transverse to F;
δ_y is the deflection at the point of application of F, along the direction y; parallel to F; and
K is the apparent stiffness of the teeth.

The theoretical magnitude of the displacements along the directions X and Y, for the teeth of the control group, in a node close to the point of application of the force, F = 100 N, predicted by the 2-D model that includes the acrylic resin, as described above in the section 2.2.2, were δ_X = 0.0336 mm, and δ_Y = 0.0023 mm, respectively. Such displacements are well above the range of displacements obtained with the previous model that includes the maxillary bone (according to section 2.2.1), instead. In both numerical models, the calculated values of δ_X are larger than those of δ_Y.

For the control group, for instance, the average maximum displacement imposed by the INSTRON machine ($\delta_{I\ MAX}$) during the tests, at the failure point, was approximately 0.546 mm. The average failure force that caused this displacement was about 1031 N, which is 10.31 times the mastication force used in the FEM models, F = 100 N. The value of δ_I is the total displacement imposed by the INSTRON machine at the failure point, in the direction of the applied force. The experimental apparent stiffness in this case is 1031N/0.546 mm, which is equal to 1888 N/mm. The theoretical mastication force, however, has an inclination of 45 degrees relatively to the coordinates X and Y, as shown in Figure 2, and the displacements given by the program ANSYS (δ_x and δ_y) are the projection of the total displacement along these directions. All these details were taken into account in the calculations of the apparent stiffness, K, according to equation (1), using the values of obtained from the 2-D and 3-D numerical simulations. In Table 3 the apparent stiffness obtained experimentally (K_{EXP}) and numerically (K_{2-D}, K_{3-D}) are presented for the three groups of teeth analyzed in this study. For the third group in particular, two different values for the elasticity modulus of the plastic roots (E = 5 GPa and E = 10 GPa) were used in the FEM simulations. Such results correspond to the last two rows of Table 3.

According to the results presented in Table 3, for the three groups of specimens included in this investigation, the experimental apparent stiffness of the teeth are significantly lower than the numerical predictions. So, the FEM simulations, in particular the 3-D models, seem to overestimate the stiffness of the structural system composed by the clamped teeth and the blocks of acrylic resin. In the buccal environment as well in "in vitro" experiments the teeth are never perfectly clamped to a structure which in infinitely rigid. So, the global stiffness tends to be higher in the numerical models, in which a group of nodes in the structure, for instance, can be assumed to be perfectly clamped.

Table 3 – Experimental and numerical predictions of the apparent stiffness (K) of the teeth.

Apparent Stiffness of the teeth, K [N / mm]			
Experimental Results		**FEM Simulations (see section 3.2.2)**	
No. of Specimens/Type	$\mathbf{K_{EXP}}$	$\mathbf{K_{2\text{-}D}}$	$\mathbf{K_{3\text{-}D}}$
8 / Control group	1888 ± 1003	2976	4611
10 / Natural root + silver	1739 ± 432	3094	4835
12 / Plastic root + silver	1075 ± 305	2018^{+}	3204^{+}
12 / Plastic root + silver	1075 ± 305	2519^{++}	3937^{++}

Obs.: $^{+}$ plastic roots with E=5 GPa; and $^{++}$ plastic roots with E=10GPa, in the simulations.

4. Discussion of the Results

The force – displacement diagrams obtained from the "in – vitro" experiments, as illustrated in Figures 5.a, 5.b, 6.a and 6.b, in which the values of F_{MAX} and those of the forces associated with the knee in the diagram of Figure 5.b were well above the mastication force, suggest that the linear elastic model adopted in this study was a correct choice to simulate the mechanical behavior of the central upper incisors.

The much lower displacements obtained from the model that includes the maxillary bone, in comparison with those concerned with the model in which the bone is replaced by a block of acrylic resin, indicate that the stiffness provided by the bone is significantly higher. However, the soft periodontal tissue that exists between the bone and the root of the tooth (Gei et al., 2002) was not taken into account in the present study. It is the intention of the authors, in due course, to include the presence of the periodontal tissue in the next FEM simulations.

The components of the mastication force, F, along X and Y, F_X and F_Y, cause very different mechanical effects in the teeth. The component F_Y produces longitudinal compressive stresses, while F_X is responsible for two additional effects: (i) transverse shear forces; and (ii) bending moments. The bending moments themselves generates tensile stresses on the palatine face of the teeth, and compression on the vestibular (or labial) face. So, the response of the teeth to F_X is similar to that presented by a cantilever beam. In both, 2-D and 3-D FEM simulations, the displacements δ_X (see Fig. 6), due to the action of F_X, were larger than δ_Y, due to the action of F_Y, mainly towards the tip of the teeth, where the difference between δ_X and δ_Y is maximum (i.e. $\delta_X >> \delta_Y$), suggesting that the bending effects are very important in the stress analysis of central upper incisors.

According to the results presented in Table 2, obtained from the 3-D FEM models, there is an indication that presence of the cast silver core in the restorations: (i) increases the equivalent von Mises stresses in the dentin, cortical bone and alveolar bone, slightly; and (ii) reduces such stresses in the enamel.

5. Final Conclusions

The main conclusions obtained from the initial results of this investigation were:

- The average experimental maximum loads (F_{max}) for the: (i) control group (1031 N); (ii) group in which the natural roots were restored with silver (1090 N); and (iii) group in which the plastic analogous roots were restored with silver (859 N), were very close to each other, indicating that after an endodontic treatment, that makes use of cast silver, the original strength of a healthy root can be recovered;

- The equivalent von Mises stresses are much higher at the periphery of the incisors rather then towards its center;

- The teeth are subjected to a combination of stresses due to the simultaneous action of longitudinal compressive forces; transverse shear forces; and bending moments, and the sign as well as the magnitude of these stresses vary from region to region. According to the 3-D FEM model, the most stressed region is the cortical bone;

- Most of the displacement takes place in the upper portion of the tooth, while the root is nearly stationary, and the displacements (δ_X) along the transverse direction (X) were larger than those (δ_Y) along the longitudinal direction (Y) of the specimens;

- The value of the mastication force, F = 100 N, fell in the very beginning of the linear elastic portion of all the diagrams F - δ obtained experimentally. So, the use of a linear analysis in the FEM models was justified; and

- The displacement field was significantly affected when the maxillary bone was replaced by the acrylic resin in the initial FEM model. The global stiffness of the second model dropped due to the higher flexibility of the resin. Conclusive results about which model is more accurate are not available yet. The influence of the periodontal tissue (thin layer of soft material around the root) on the global stiffness must be taken into account in future studies.

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