

The FEA Study of the Biomechanic Behavior of Canine Reconstructed with Composite Resin

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The aim of the finite element analysis (FEA) is to determine the stress and deformation state of all elements of four mechanical assemblies under certain loading and fastening conditions of the structure. The structure of the finite element analysis consists of GIC and 4 geometric variables (no bone loss, 1 surface radial loss, 2 surfaces and circumferential loss). Geometric reconstruction of simulated elements is done based on the X-ray scan images. The DICOM image collection is imported into Mimics 10.01, where two color layers are applied, which are then transformed into volumes. Surface integrity was accomplished using Geomagic Studio 2013 software. Subsequent to the reconstruction, classical geometric modeling was carried out using the SolidWorks 2013 CAD environment. Four geometric models were made and the assembly described above was inserted. Finite element analysis was performed with the Ansys 13 software. For resin composite restorations, in the case of circumferentially bone loss, the restoration pressure drops due to increased tooth elastic deformation possibilities. In case of bone loss on one face and two sides of the tooth, there is a strong pressure on the cementum-bone interface, due to the bending effect that occurs. Pressures in dental root restorations are higher in the case of reconstruction using resin composite.

Keywords: finite element analysis, composite resin, root caries

In recent years, composite resins have seen a strong development on a large scale. This is due to their superior adhesion properties to both enamel and dentin. Furthermore, composites are superior from an aesthetic point of view because they can be adjusted to best mimic the natural color of the patient's teeth [1-4].

Experimental part

Geometric patterns achievement

Geometric reconstruction

In order to achieve a numerical simulation, it is necessary to construct a 2D or 3D geometric model on which a series of contouring conditions can then be established. In order to achieve a genuine model, geometric reconstruction of simulated elements is required based on the X-ray scan images. The DICOM image collection was thus imported into Mimics 10.01, where two color layers

were applied (fig. 1 and fig. 2). Each of these corresponds to a segmentation interval: one corresponding to hard tissues (cortical and spongy bone, set interval 870-2800 HU) and soft tissues respectively with a range of 80-280 HU. Image segmentation operation allows the conversion of 2D pixels from grayscale DICOM images into object pixels [5-7].

$$HU = 1000 \times \frac{\mu - \mu_{water}}{\mu_{water} - \mu_{air}} \quad (1)$$

The colour layers were then transformed into volumes. Due to the large number of artifacts present on any X-ray scanning, the quality of the resulting volume is very low. It contains a very large series of surfaces of the following types: spike, self-intersecting, discontinuous, surfaces that make it impossible to place the contour conditions correctly (fig. 3).

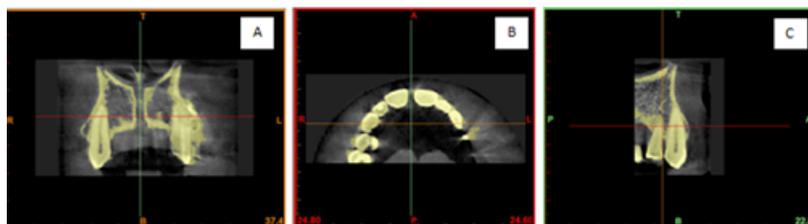


Fig. 1 Color layer applied

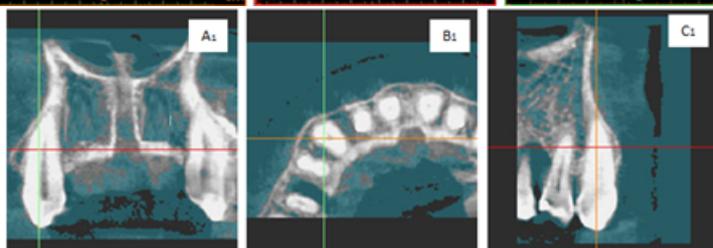


Fig. 2 Color layer applied to low density tissues (soft tissues)

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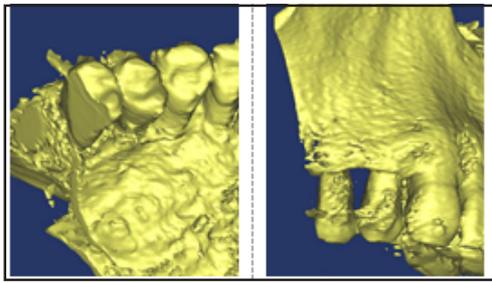


Fig. 3 Primary 3D Reconstruction of a Canine Area - Isometric Views

Surface integrity was accomplished using Geomagic Studio 2013 software. In this work environment, the canine extracted from the reconstruction software was imported as a cloud of points.

Because of surface discontinuities, some areas required redesign of the surfaces. In cases where the angles between the triangular surfaces involved do not exceed a critical value, the operation can be performed automatically. In cases of strong network distortion, the repair is done manually (fig. 4). After filling up all the discontinuous zones, a re-discrete of the entire canine side surface was made to obtain a smoother volume. Each of these operations is done with loss of shape and dimensions. But it is the necessary compromise that ensures the possibility of carrying out a numerical simulation, namely the prior generation of a volume mesh.

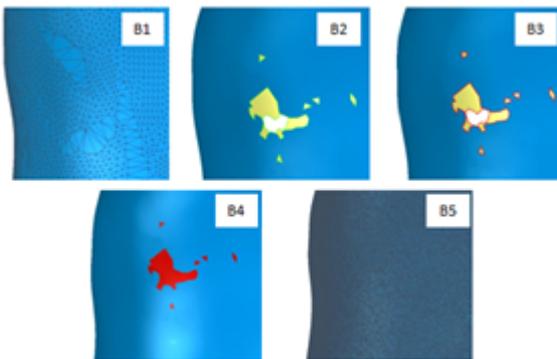


Fig. 4 Removal of self-intersecting triangles and surface meshing refinement: B1-coarse mesh, B2 - eliminated surfaces, B3 and B4 filling surfaces, B5 fine meshing

The refinement of the geometric model was obtained by increasing approx. 3 times the number of triangles in the surface (from 95687 to 282276). Thus, the resulting volume obtained a smooth aspect, valid for the numerical analysis (fig.5 C).

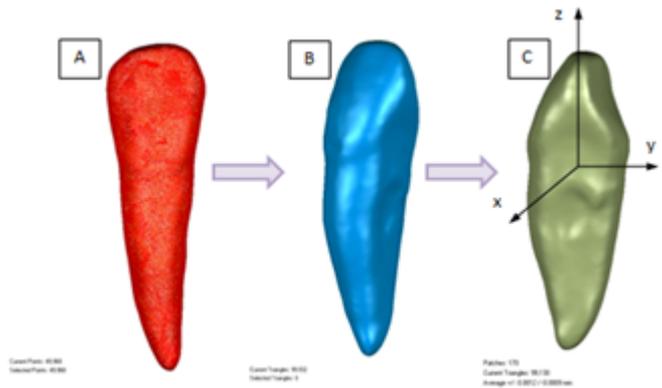


Fig. 5 Stages of geometric transformation from dot cloud (surface) to dark (solid)

Figure 5 shows the three main steps required to convert from dot cloud (A) to dark volume (solid C). The intermediate step (B) represents the stage of the surfaces, where the necessary corrections have been applied to ensure an integral form.

Classic geometric modeling

Subsequent to the reconstruction, classical geometric modeling was carried out using the SolidWorks 2013 CAD environment. Boolean operations were performed at this stage, separating the geometric model obtained by reconstruction into 4 conjugated solid volumes, each of which had an anatomical structure:

- Dentine model figure 6 A;
- The enamel model figure 6 B;
- The cementum model figure C;
- Pulp chamber model figure 6 D.

Root caries simulation was performed by a cutting operation with a profiled surface. The geometric operation was applied to both the solid dentine and the solid cementum. The shape of the extrusion surface corresponds to the considered root caries section (fig. 7).

The aesthetic restoration element was geometrically performed as a conjugated form of the root decay profile. In this way, it was possible to establish the coincidence relationship between the dentine alveolus, respectively the cementum and the geometry of the root therapy.

The assembling of all elements was accomplished by establishing relationships such as alignments, coincidences, concentricities, parallelism, etc. The RG/GR denomination for enamel, dentin and cementum indicates that these two elements were obtained by geometric reconstruction (GR), and MG/CM are objects obtained by classical modeling (CM).

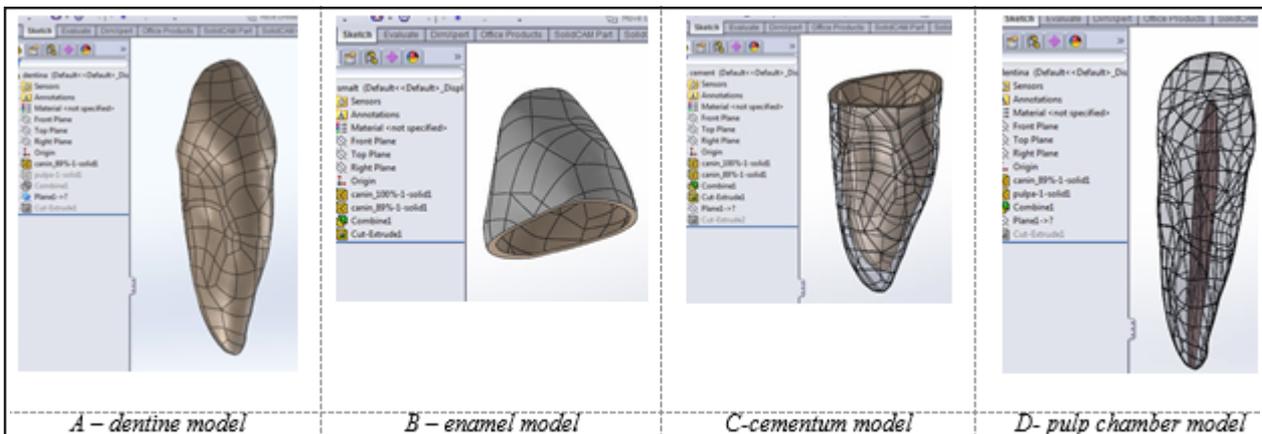


Fig. 6 Anatomic volumes obtained by Boolean decrease

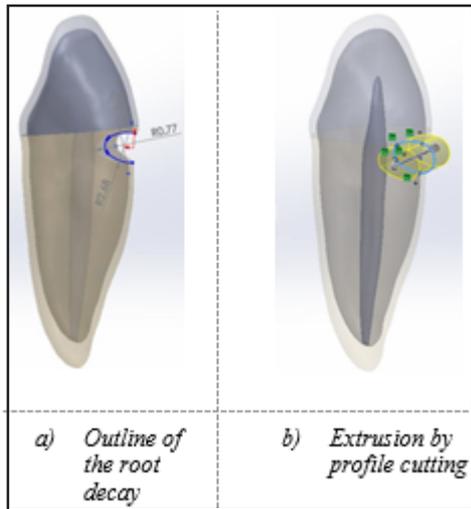


Fig. 7 Fault generation operation

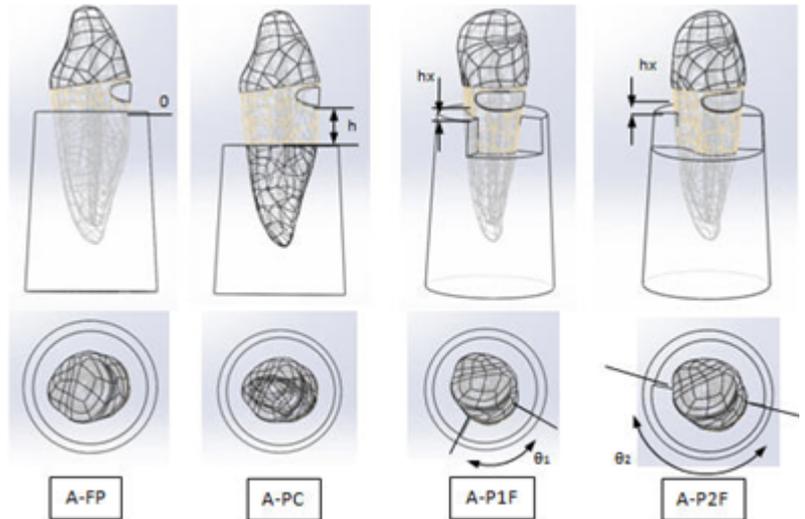


Fig. 8 Relative positioning of the tooth against the four types of bone alveoli

Nr.	Type of bony interface	Coding	Height to root therapy area (h) [mm]	Lost section angle θ [°]
1	Without osseous/bone loss	A-FP	0.0	0
2	With circumferential loss	A-PC	5.0	360
3	With 1-sided radial loss	A-P1F	$hx_1 = 3.5$ $hx_2 = 3.0$	90
4	With 2-sided radial loss	A-P2F	$hx_1 = 3.5$ $hx_2 = 3.0$	180

Table 1
CODING AND POSITIONING DIMENSIONS

In order to perform numerical simulations for four types of bony alveolus geometry, four geometric models were made in which the assembly described above was inserted. The relative positioning characteristics of tooth assembly with the osseous alveolus/ alveolar bone, as well as the established codings are shown in table 1 and figure 8.

Finite Element Analysis

Finite element analysis was performed with the *Ansys 13* software. The 3D exported models from Solidworks were imported into the Geometry module of the program as *.igs files. Prior to establishing the contour conditions and the mutual contacts between the solids that make up the ensemble, the materials to be used have been defined in the analysis database [8-13]. Their mechanical properties were extracted from the literature and presented in table 2.

The purpose of the finite element analysis was to determine the stress and deformation state of all elements of the four mechanical assemblies under certain loading and fastening conditions of the structure. The structure of the finite element analysis consists of composite material and 4 geometric variables (no bone loss, 1 surface radial loss, 2 surfaces and circumferential loss).

Establishing contour conditions

The operation of making the structure discrete was carried out with the help of the tetrahedral elements of constant dimensions (fig. 9, a). The dimension of the element was chosen in such a way that the results of the analysis would reach convergence. The number of nodes and elements of the structure were: 313946 and 195434 respectively.

The contacts between the individual mechanical elements (alveolus-cementum-dentine-root canal-

Table 2
MECHANICAL PROPERTIES OF THE MATERIALS USED IN THE ANALYSIS [8-10]

Material/Property	Density [kg/m ³]	Young Module [MPa]	Poisson coefficient	Mechanical strength of adhesion [MPa]
Composite resin	1590	16500	0.24	-with enamel: 15-25 -with dentine: 30-42
Tooth enamel	2750	74000	0.23	
Cementum	1890	3400	0.32	
Dentine	2000	17000	0.30	
Pulp	1200	0.003	0.45	
Alveolar bone	1820	19000	0.35	

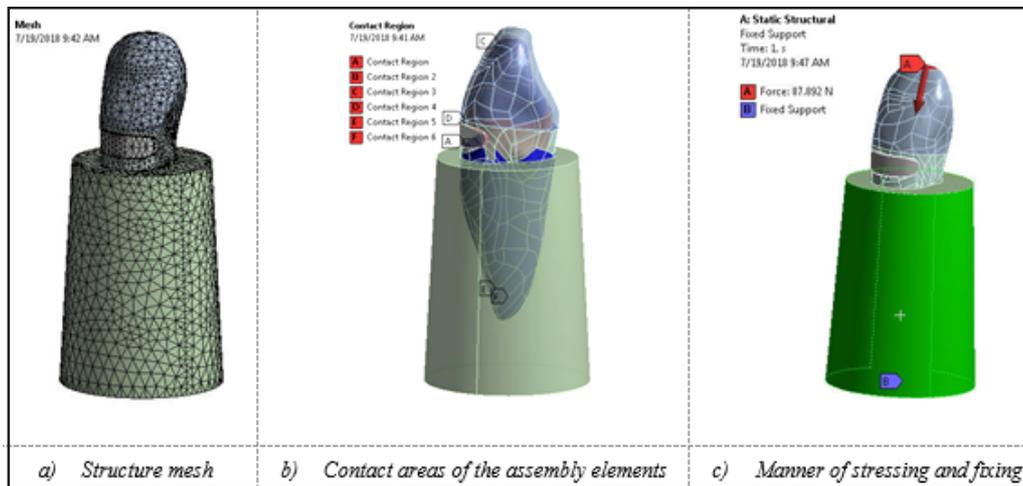


Fig. 9 The contour conditions of all models, exemplified on the A-PC model

enamel-dental pulp) were defined in accordance with mutually tangent surfaces (fig. 9, b). The contact type was *bounded*, meaning that it does not allow any movement or sliding at the interfaces.

The loading and fixation manners of the structure were defined according to biomechanical studies in the literature. The values of the applied loading forces and their directions are decisive for the values of the pressures that are born in the studied model. According to the literature, the canine loading during mastication is 130-340N. Of course, biting force values are much higher, of 1250-1300N, and the effect of such a bite will produce higher pressure values at the composites restoration level [14 -16].

The loading force used in the study was $R = 90\text{ N}$, defined as components following the 3 directions (Figure 9) of the coordinate system as follows:

$$\begin{cases} \vec{F}_x = 20 \cdot \vec{i} \\ \vec{F}_y = -30 \cdot \vec{j} \\ \vec{F}_z = 83 \cdot \vec{k} \end{cases}$$

$$\vec{R} = \vec{F}_x + \vec{F}_y + \vec{F}_z$$

$$|R| = \sqrt{F_x^2 + F_y^2 + F_z^2} = 90.5\text{ N}$$

Results and discussions

Figure 10 presents the results of the numerical simulation of the biomechanical behavior of the A-FP assembly, in the case of composite resin restoration. The recorded pressures and deformations are presented as color maps and variation graphs according to their values in the most requested area.

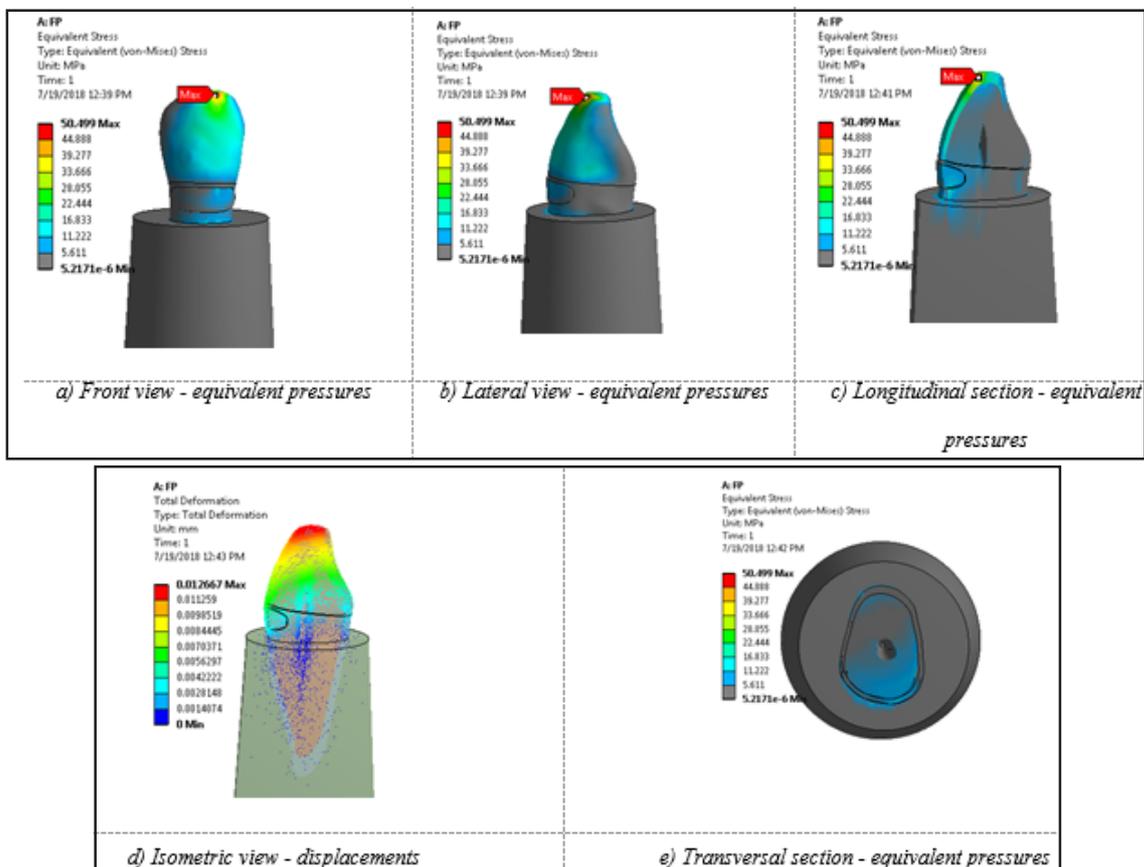


Fig. 10 A-FP Model simulation

In the case of bone loss on the circumference, the restoration pressure drops due to increased tooth elastic deformation possibilities (fig. 11). It can also be seen in

this case that the deep volume of the tooth is mechanically unsolicited and cannot contribute to mechanical strength.

Figures 12 and 13 present simulation results in case of bone loss on one face and two sides of the tooth. In both

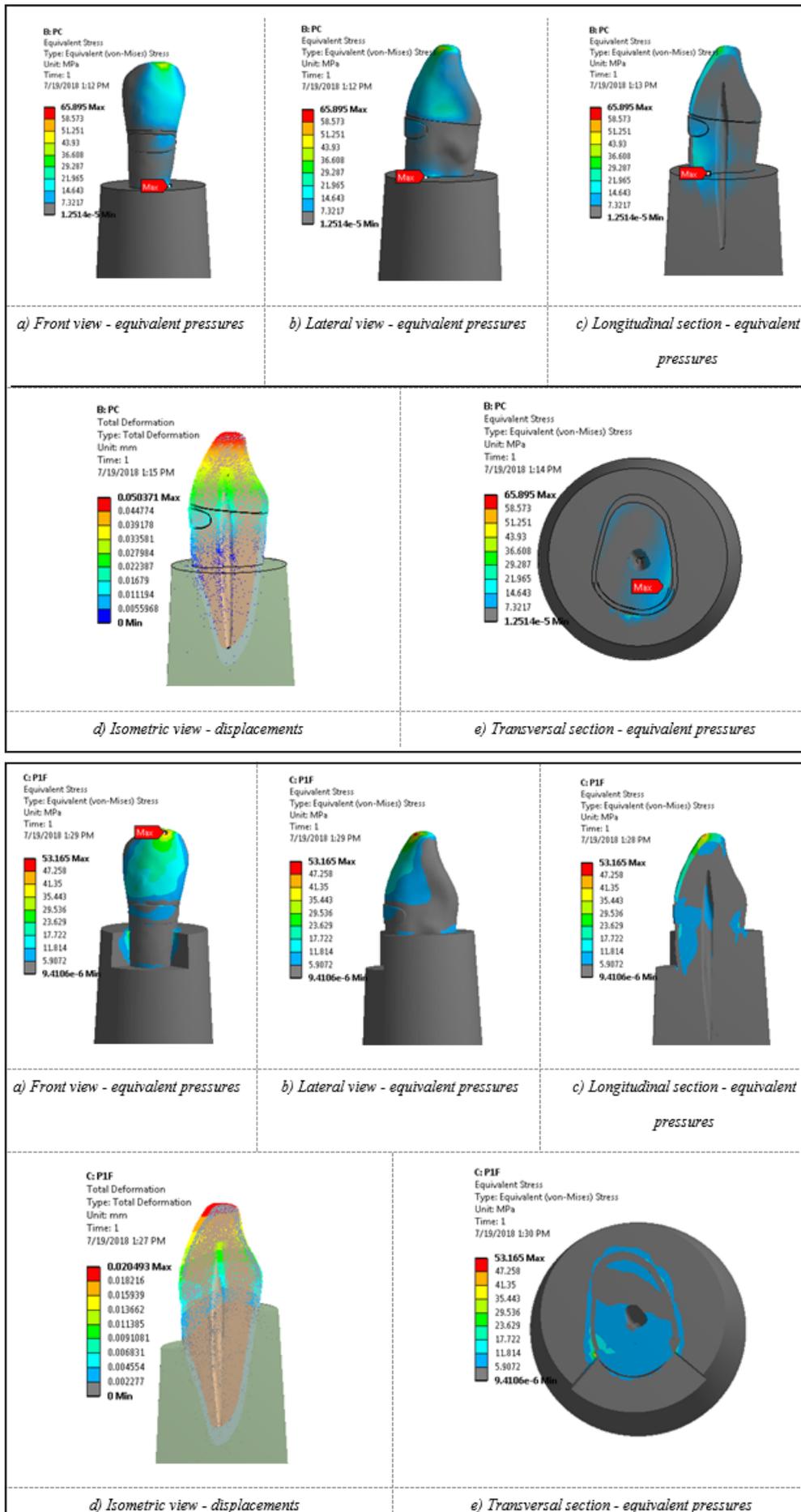


Fig. 11 A-PC Model simulation

Fig. 12 A-P1F Model simulation

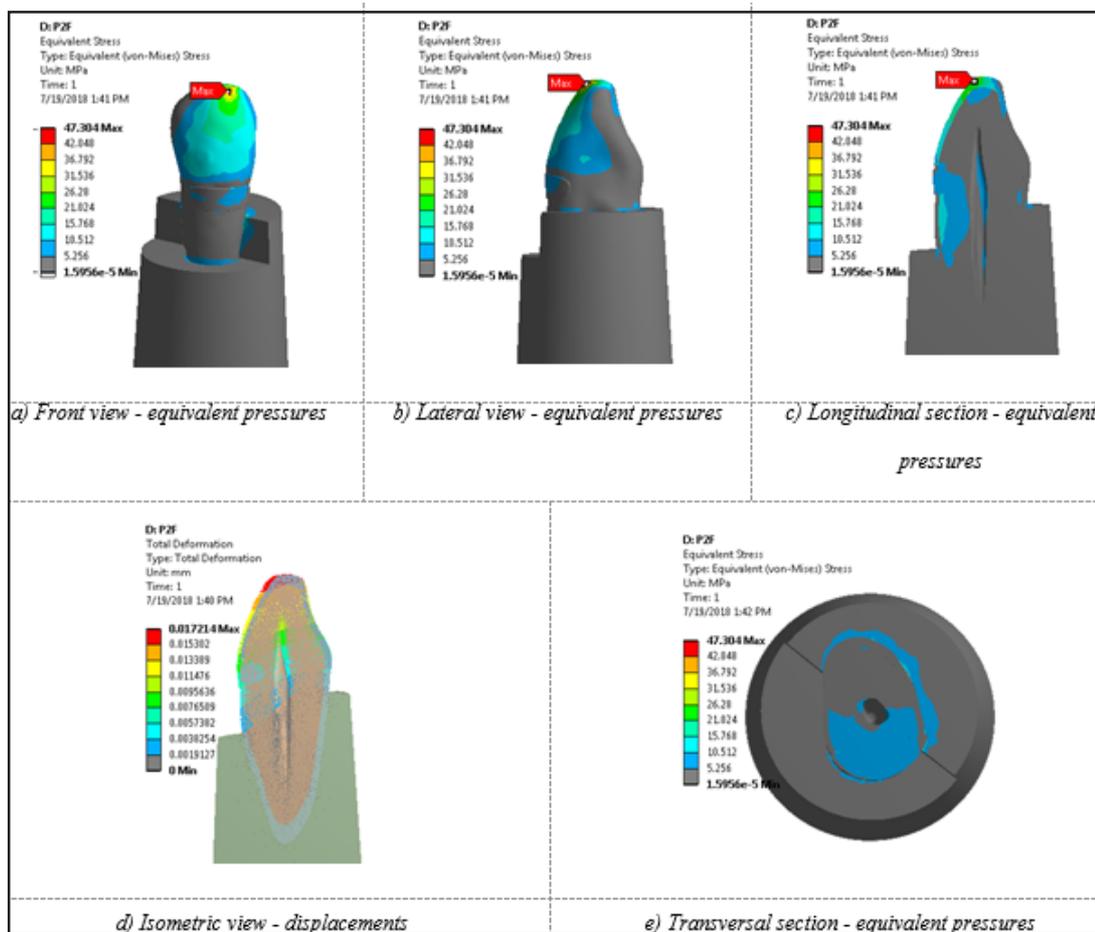


Fig. 13 A-P2F Model simulation

Table 3
MEAN AND MAXIMUM VALUES OF THE STRESS IN THE MOST DEMANDING AREAS

Structure type	SIMULATED SITUATIONS				σ [MPa]
	FP	PC	P1F	P2F	
Aesthetic restoration	20.27±5.43	14.08±3.42	14.22±3.30	14.38±3.45	med. ±SD
	28.64	19.99	19.96	20.32	max.
Bone tissue	28.19±13.29	54.15±24.10	45.51±16.53	53.69±21.58	med. ±SD
	65.18	123.38	121.82	128.47	max.
Dentine	16.90±5.00	36.63±11.84	32.92±20.08	26.35±18.14	med. ±SD
	42.36	69.33	83.22	61.23	max.
Enamel	49.90±12.15	49.37±12.12	50.69±13.88	49.39±12.12	med. ±SD
	111.65	67.88	71.44	67.88	max.
Cementum	8.28±2.26	13.66±4.05	5.81±4.02	3.58±1.58	med. ±SD
	12.56	20.03	14.22	7.54	max.

cases (more pronounced in the second) there is a strong pressure on the cementum-bone interface, due to the bending effect that occurs. This effect may disappear only if the stress is applied perfectly in the symmetry longitudinal axis of the tooth, which is virtually impossible to achieve.

It can also be observed that the alveolar bone, cementum and dentine exhibit more pronounced pressure leaps than in restoration and enamel geometries, the latter displaying a uniform distribution pattern. The values of the maximum, mean stresses and standard deviations are presented in table 3.

The maximum pressures are relatively high in this simulated case due to the properties of the resin composite. Its high rigidity influences not only the state of pressure in

the component to which it has been assigned (aesthetic restoration), but also by the effect of stresses propagation, it also affects the other adjacent components. We will therefore see higher pressures for all components of the assembly.

Pressures in aesthetic restoration are higher in the case of reconstruction using GICs.

When restoring reshaped abfraction lesions with Giomers Beautifil II and Beautifil FO2, assessing the behavior of the adhesive layer and Giomers by means of FEA, showed that at a pressure of 90 N, there is an uniform tension distribution in both forms of Giomer materials especially for Giomer Beautifil FO2, but the adhesive system's tensile strength which is approximately 25MPa is reached at this value. Anything over this value faces a risk for the adhesive to detach [17].

It can be considered that particular types of restoring materials should be used in particular lesions to be restored, depending on the location of the lesion and the elastic characteristics of the materials and tooth structure (dentine or enamel) [18,19]. Pressures in aesthetic restoration are higher in the case of reconstruction using composite resin.

Finite element analyzes are widely used today in dental researches to simulate and analyze the various clinical situations to identify areas of risk in which dental materials or bone jaws yields to stress and strains. [20-25]

Conclusions

Due to the mechanical strength of the higher adhesion of the resin composite (30-42 MPa with dentine) it can be stated that a load of 90 N the resin composite restoration is within the safety limits.

According to the different adhesion properties with the cementum respectively the dentine, it can be said that the association resin composite restoration is favorable to the dentine areas.

Independently of the material used for reconstruction, the values of the equivalent stresses are higher when the alveolar bone is complete. Decreasing pressures in aesthetic restoration with alveolar bone loss is due to the increase in the possibility of elastic deformation of the tooth as a whole.

The most tense area of the enamel remains at comparable values regardless of whether or not the alveolar bone is lost. This is due to the fact that the mechanical stress was applied each time on the same surface, had the same value, respectively, in the same direction.

The maximum mean stress values are recorded in the enamel and the alveolar bone due to their higher modulus of elasticity compared to the other elements of the assembly.

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