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FEM modeling of a tooth behavior depending on mineralization state

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Abstract. The problem of mineralization of bone structures has been a subject of research and discussion for a long time due to the influence it has on the functioning of the entire human system. In practice, to improve the concentration of minerals in the bones, there are currently multiple dietary supplements that act on them. However, less research has been done on the chemical composition of teeth and how these mineral concentrations influence their behavior. The present research refers to the way in which a tooth behaves under the action of forces acting on its enamel surface. For this, the finite element method was used, which lends itself very well in this situation where, based on the specialized literature, mechanical properties and forces acting on a tooth were used as input data. Its mechanical properties, such as the modulus of elasticity, have different values for the situation of a normal tooth or a demineralized one. The article thus presents the state of tension and deformation that appears in a tooth in the two situations presented, resulting in interesting conclusions in this sense useful to a practitioner in the field of dentistry.
Keywords: *mineralization, tooth, FEM, displacement, stress*

1.Introduction

Many factors influence the strength of your tooth enamel, and demineralization and remineralization are among the many. Throughtout the life, teeth are at high risk of demineralization, due to the fact that they are in direct contact daily with food, drinks and microbiota of the mouth. However the body continuously struggles to alleviate the impact of demineralization through a process called tooth mineralization.

Demineralization is a natural process and during the first stage, your teeth lose their vital minerals. When this happens, you'll notice white spots on the surface of your teeth. The minerals lost from these areas indicate the beginning of tooth decay. If tooth decay continuous and you fail to take any preventive measures, there will be further damage to the enamel. Now what you'll see is white spots on the tooth turning to dark brownish color. Weakened enamel is also prone to dental cavities or caries, and the result is tiny holes in your teeth. The layer under the tooth enamel is dentin, which is softer and can more easily be damaged by the mouth acids. This means that if tooth decay reaches the dentin, it will cause rapid damage. [1] On the other hand, tooth remineralization is a natural repairing process that covers both prevention and cure of demineralization-it can be stopped or even reversed, especially in the early phase. An important role in prevention is played by saliva, diet control, probiotic bacteria and fluoride therapy. When your teeth are remineralizing, the eroded tooth enamel is being repaired, which helps prevent cavities. By definition, tooth enamel remineralization means giving the essential minerals back to the enamel to strengthen the teeth and fight against cavities and other oral issues. Saliva plays a vital role in neutralizing the harmful acids in the mouth, providing your teeth phosphate and calcium ions to remineralize your teeth. If saliva is circulated continuously, it can help prevent the debris from accumulating and eliminates the bacteria that can produce mouth acids. When bacteria are removed, your tooth enamel can absorb the available calcium. So, a healthy supply of saliva can help remineralize your teeth. In conclusion, the processes of demineralization or mineralization of the teeth, like all bones, play an extremely important role in the general health of the human organism [2].

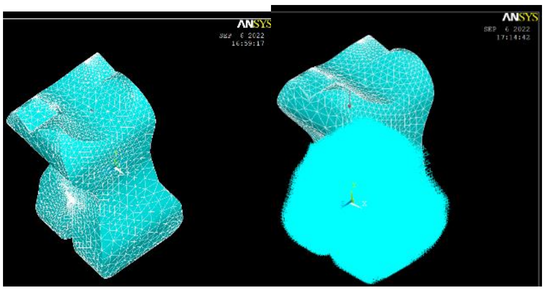
2. Finite element modeling of the behavior of a normal tooth compared to a mineralized one

2.1 Input data for FEM model of the tooth

The mineralization process that takes place throughout the human body is thus reflected, similarly, in any bone structure. In this sense, in order to verify the changes produced by the mineralization process, the behavior of a tooth in its normal structure and in the situation in which it is mineralized will be studied. In general, the mechanical properties of a mineralized tooth increase by approximately 70-80% compared to those of a normal tooth. The studies on the mechanical properties of the teeth are very numerous, as are the methods by which they were determined. Ya-Rong Zhang*, Wen Du*, Xue-Dong Zhou and Hai-Yang Yu present a well-done study in which the properties of the different areas of the tooth are presented: dentin, enamel and pulp [3]. Similarly, Paul Zaslansky, Asher A. Friesem, Steve Weiner studied the areas at the interface of dentine and enamel [4]. Methods for determining the mechanical properties of the three areas of the tooth have been well studied and realized experimentally by KJ Chun, HH Choi, and JY Lee in [6] or R. G. CRAIG, F. A. PEYTON, and D. W. JOHNSON [5]. Regarding the values of the mechanical properties in the studied articles, in the present study the values shown in table 1 were used, in which the density values calculated by Reina Tanaka, Yo Shibata, Atsufumi Manabe, Takashi Miyazaki [5] or by Reina Tanaka, Yo Shibata, Atsufumi Manabe, Takashi Miyazaki [8]. To create the mathematical model, a meshed geometry was used, which is presented in figure 1 a.

Table 1 Mechanical properties of the enamel, dentine and pulp in the studied cases (normal od mineralised tooth).

	Young modulus E	Poisson coefficient	Density [Kg/m^3]	Young modulus for minersalised tooth E
Enamel	88 [Gpa]	0.3	3000	125 [Gpa]
Dentina	19.7 [Gpa]	0.3	1840	35 [Gpa]
Pulp	2.07 [Mpa]	0.45	100	2.07 [Mpa]



a. b.

Figure 1 a - Meshed volume of the tooth; b – inputa data of the model: Force F and displacement presentation

The meshing was done using the ANSYS program with the SOLID187 discretization element, which provides as output data the displacements of the structure under the conditions of the application of a force and the stress state that develops in the body, also as a result of the application of a system of forces.

3. Case study

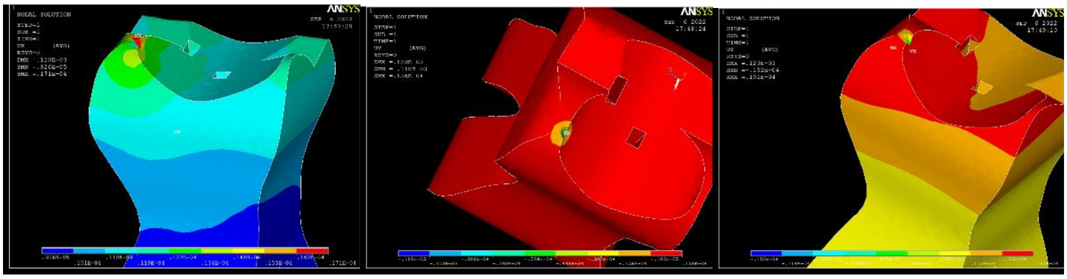
The present study was carried out, taking into account several variables. As previously presented, the first variable is the degree of mineralization of the tooth. The second variable is represented by the value of the forces applied to the tooth surface during the mastication process. In this sense, there are currently many researches that offer different values of the applied forces that take into account the position of the tooth, the type of food, the type of force application (gradual or with impact), etc. In his work Rosa Alicia Hernández-Vázquez, Beatriz Romero-Ángeles, Guillermo Urriolagoitia-Sosa, Juan Alejandro Vázquez-Feijoo, Ángel Javier Vázquez-López, and Guillermo Urriolagoitia Calderón study the masticatory forces applied as pressure and measured in N/m^2 [9]. At the same time, the mechanical properties of the structure of a tooth are presented, close in value to those used in this study. In the work Masticatory Force in Relation with Age in Subjects with Full Permanent Dentition: A Cross-Sectional Study [10], Ottavia Poli, Licia Manzon, Tarcisio Niglio, Evaristo Ettorre and Iole Vozza do a complete analysis, by age group, of the forces which appear during mastication in both men and women. Taking into account the studied bibliography, the values of the forces acting on the tooth were defined as F1 = 124 N and F2 = 190 N. The direction, meaning and position relative to the target surface of the studied forces are shown in figure 1b.

As a result of the mechanical analysis carried out with the help of ANSYS software, images were obtained for each loading case and for each type of tooth. Since the space of the article does not allow displaying all the images, in the following only the results obtained in the case of the action of the force F2 = 190 N will be presented. In the case of the action of the force F1 = 124 N, the displacement results are presented in Tab.2.

Table 2 Displacement values for normal teeth in the two load cases

	Tn F=124 N	Tn F=190
Ux [mm]	0.014	0.017
Uy [mm]	0.073	0.011
Uz [mm]	0.016	0.019

Thus, figure 2 shows the displacements on OX, OY, and OZ axis in the second loading case for the normal tooth, and figure 4 shows the displacements resulting from the action of the force F2 = 190 N for the mineralized tooth.



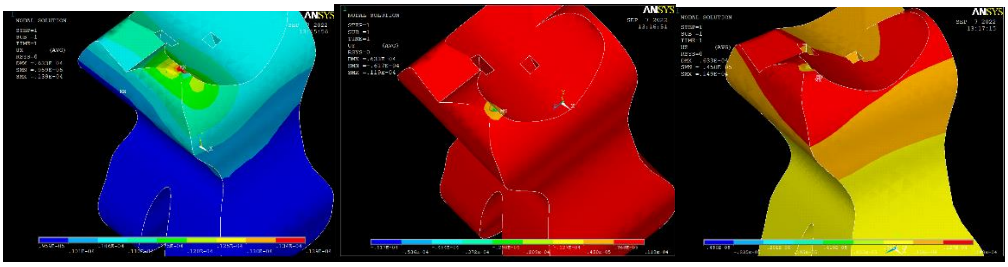
a. b. c.

Figure 2 Displacements: a.- UX, b. - UY, c. - UZ under the action of the force F = 190 N for a non-mineralized tooth

For the mineralized tooth, table 3 shows the displacements of the structure in both loading cases.

Table 3 Displacement values for mineralized teeth in the two loading cases

	Tm F=124 N	Tm F=190 N
Ux [mm]	0.012	0.014
Uy [mm]	0.036	0.061
Uz [mm]	0.013	0.015



a. b. c.

Figure 3 Displacements UX, UY, UZ for F=190 N for a mineralized tooth

As can be seen in all four situations, the tooth undergoes movements of the order of hundredths of a millimeter, noting that:

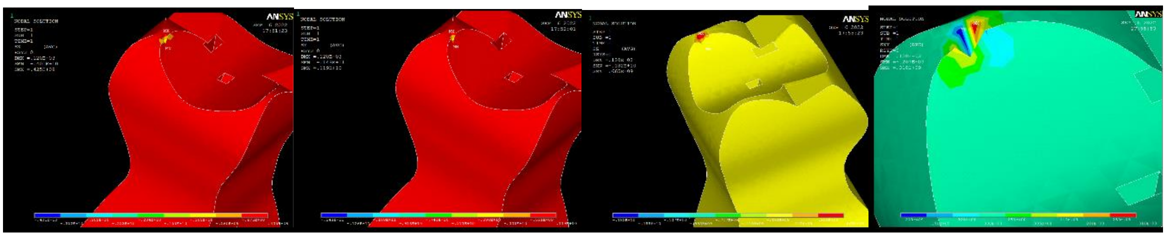
- In the case of applying force F2, the displacements are greater for both types of tooth;
- In the case of tooth mineralization, the calculated displacements are smaller than in the case of a normal tooth.

The second category of results refers to the stress map that appears in the structure of the tooth. At the present time in the theory of material resistance, the state of stress cannot be defined using a single criterion so that, in order to obtain a complete picture of the integrity of a structure, several types of stress must be analyzed such as those corresponding to the axes OX, OY, OZ, the shear stresses in the XOY, XOZ and YOX planes, such as the S1, S2, and S3 type stresses that describe the predominantly tensile stress state, the balanced stress state between extension and compression, respectively the compression stresses. In this sense, figure 5 shows the stresses Sx, Sy, Sz, Sxy, Syx, S1, S2, S3 characteristic of the normal tooth on which the force F2 = 190 N acts, while table 3 shows the mechanical stresses that appear in both loading situations.

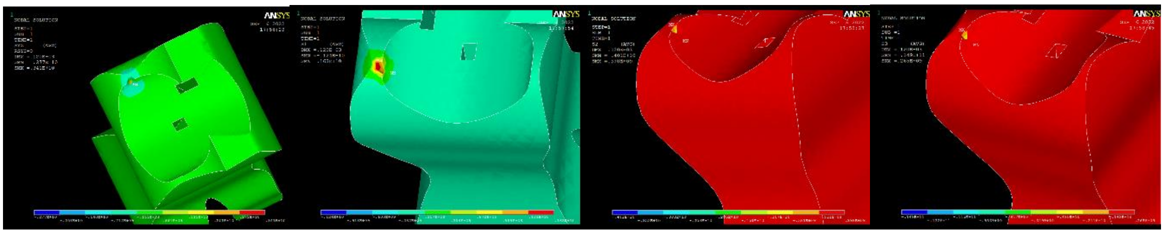
As can be seen, the values of the stresses that appear in the tooth structure are close to the values of the Young modulus of the dentine and being somewhat lower than the modulus of elasticity of the enamel (according to Tab. 1). This level of stress is an important one, even if the modulus of elasticity of the materials in the tooth structure is not exceeded. The stress appeared as a result of the application of a chewing force corresponding to the crushing of a crust of bread. But if this force is exceeded in other specific mastication situations, the tensions will increase and may even exceed the elasticity modules of the dentine and enamel. As a result, cracks or even cracks may appear in the tooth structure.

Table 4 Mechanical stress maximum values in the case o applied force F1 = 124 N (mastication of a meat loaf) and F2 = 190 N (mastication of crust of bread) for a normal tooth

	Tn F=124 N	Tn F=190 N
Sx [Gpa]	2.6	4.1
Sy [Gpa]	9.3	14
Sz [Gpa]	1.1	1.8
Sxy [Gpa]	2	0.31
Syz [Gpa]	2.2	2.29
Sxy [Gpa]	2	0.31
S1 [Gpa]	1.06	1.63
S2 [Gpa]	2.6	4
S3 [Gpa]	9.7	19



a. b. c. d.



e. f. g. h.

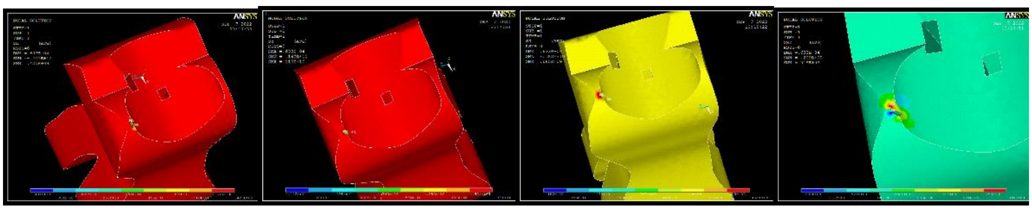
Figure 4 Stresses calculation: a - Sx, b - Sy, c - Sz, d - Sxy, e - Syx, f - S1, g- S2, h- S3 at F=190 N for a normal tooth

The mineralization of the teeth implies, as is natural, the increase of their mechanical properties. The presentation of the maximum values of the stresses that appear in the mineralized tooth in the case of loading with force F1 = 126 respectively F2 = 190 N that occurs when chewing a bread with a hard crust is done in table 5. As can be seen from the comparison with the stress states presented in table 3, in the case of loading with force F1 = 124 N, the stresses in the tooth structure are very similar. In the case of loading with force F2 = 190 N, however, a decrease in the maximum stress values is observed in the case of tooth mineralization. The decreases are not very big, but they still exist. It can be emphasized, however, the presence of important stresses, close to the value of the modulus of elasticity of the dentin, which must be taken into account. The modulus of elasticity of the enamel, being higher, shows an elastic behavior, in the case of a normal mastication process, but in the situation where the forces accidentally exceed the studied values and the integrity of the enamel is not perfect, the situation can change. Cracks or cracks may appear and the integrity of the tooth may be endangered.

Table 5 Mechanical stress maximum values in the case o applied force F1 = 124 N (mastication of a meat loaf) and F2 = 190 N (mastication of crust of bread) for a mineralized tooth

	Tm F=124 N	Tm F=190
Sx [Gpa]	2.6	4
Sy[Gpa]	9.3	14
Sz[Gpa]	1.2	1.8
Sxy[Gpa]	0.2	0.32
Syz[Gpa]	2.2	3.4
Sxy[Gpa]	0.2	0.31
S1[Gpa]	1	1.6
S2[Gpa]	2.6	4
S3[Gpa]	9.7	14

Next, figure 5 shows the stress states that appear in a mineralized tooth when a concentrated force F2= 190 N is applied.



a. b. c. d.

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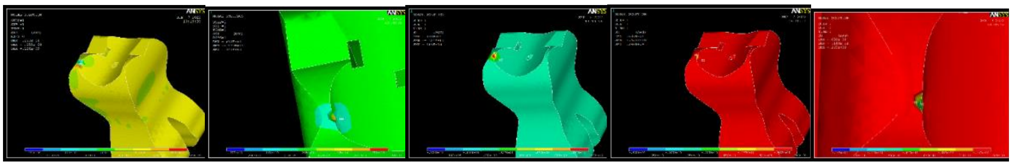

e. f. g. h. i.

Figure 5 Type of stress: a - Sx, b - Sy, c - Sz, d - Sxy, e - Syx, f - S1, g- S2, h- S3 at F=190 N for a normal tooth

4. Conclusion

The mineralization process contributes to changing the properties of bones or teeth in the human body. In addition to other benefits that are exclusively part of the medical field, engineering can study what happens to bone structures that undergo such beneficial changes. Teeth have a relatively similar structure to that of bones and are characterized by mechanical properties that can be evaluated through mathematical engineering models. In the presented article, the behavior of a tooth was studied in the situation in which it underwent a process of additional mineralization and in the situation in which this process did not take place. As input data in the modeling and simulation software, two cases were considered in which two forces acted on the tooth, one during the mastication process of a piece of meat and a force that appears in the situation of masticating a piece of rind bread. These situations are considered normal in a mastication process and the results obtained both for the mineralized tooth and for the normal one, prove an elastic behavior, at the limit, immediately below the modulus of elasticity of the dentin or enamel.

It is important to note that in the case of a mineralized tooth, its displacements are smaller, while the state of mechanical tension, if the applied force is the highest, is lower than in the case of a normal tooth. From the point of view of mechanical stress states, it can be said that the mineralization process of a tooth makes its effect felt in the situation where the tooth is subjected to more difficult functional situations, which represents an important benefit. In normal functional situations, big differences between the two types of teeth are not felt. In order to characterize the state of mechanical stress that appears in the presented situations, figure 6 shows a graph in which:

- horizontally, the studied stress types are presented;
- vertically, the stress values

With colors are presented: TM F124, F190 – the values for the mineralized tooth on which the force acts F=124 N respectively 190 N; TN values corresponding to the normal tooth.

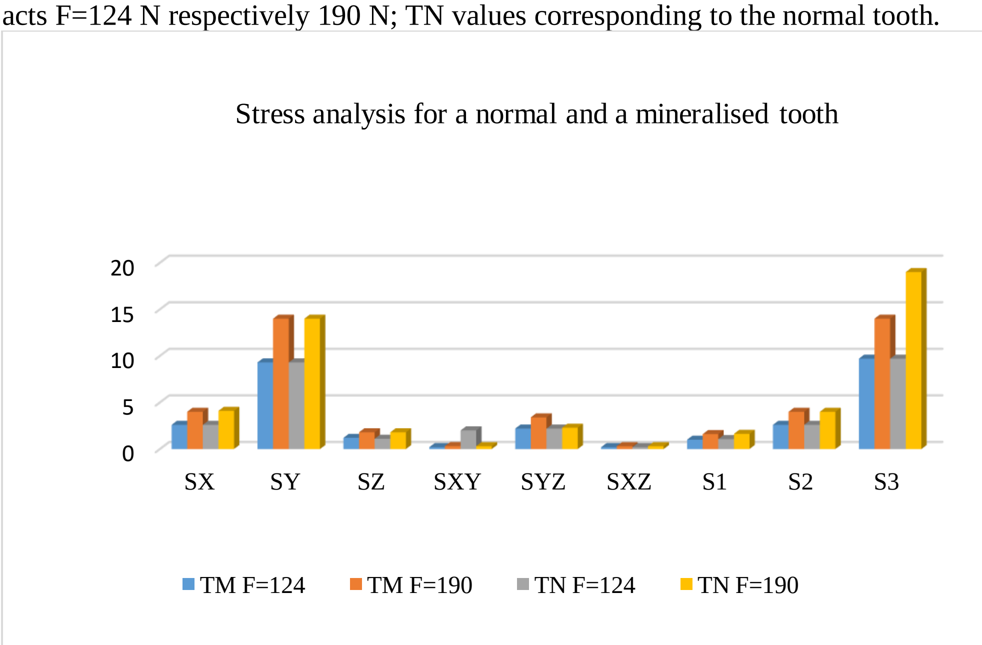

Figure 6 Stress analysis for a normal and a mineralised tooth

As can be seen, the highest values of the stresses are found in the case of the stresses on the OY axis, which is the axis on which the chewing force acts, and the S3 type stresses, which represent the compression stresses, the force representing a compression on the tooth. In general, the stresses corresponding to the TM mineralized tooth are lower than in the case of the normal tooth. The smallest stresses are the shear stresses in the XOZ plane, so the rotation of the teeth in this plane cannot produce important effects.

In conclusion, it can be said that the mineralization process is beneficial to the structure of the teeth, their resistance being observed especially at higher, potentially critical forces that may appear in the mastication process.

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