STRESS-STRAIN ANALYSIS OF RESTORED FIRST MOLAR TOOTH WITH CAVITY OF CLASS II

Jiří Valášek*, Petr Marcián*, Kamil Řehák*, David Krpalek*, Zdeněk Florian*

The presented paper is focused on the stress – strain analysis of the restored tooth. For this problem computational modelling was chosen using the finite element method. The tooth is modelled from dentin and dental enamel with a class II cavity. The size of the dental cavity is considered in three sizes and three shapes. For restoration two types of filling materials were used. A physiological model of the tooth was created as well. Force was prescribed on the occlusal surface of the tooth. The analysis of results shows that from the different filling materials, and their interaction with the dental tissues, amalgam is from a mechanical aspect the best material for the restored tooth in the molar segment.

Keywords : *finite element method, restored tooth, class II cavity, amalgam, composite resin*

1. Introduction

Recently there have been only a few people who can boast of healthy teeth without any intervention by a dentist. Teeth are an integral part of the oral cavity and each person uses them several times a day for receiving and processing food. The next important role is their irreplaceable place in the overall personal appearance. In case of the extensive damage or loss of the tooth it is either possible to insert a dental implant into a vacant place [1], [2] or use a dental bridge. Both of these solutions are very expensive and time consuming. For these reasons it is very important to take care of the teeth and mouth and keep them in good condition. Although the teeth consist of the most resistant and hardest material in the human body, it can still be damaged by mechanical, chemical and biological processes. The most common damage of the dental tissues is dental caries [3]. The treatment of dental caries belong to the branch of restorative dentistry. Dental caries is removed by using dental instruments and the newly vacant place is ready for the application of a filling material. This procedure is called tooth restoration. A well executed restoration of the tooth helps to prevent the spread of further dental caries and it maintains the basic function of teeth like separating and crushing food. In this activity the teeth are significantly mechanically loaded. Restoration of the teeth significantly changes the coherence and mechanical properties of the impaired dental tissue, which also affects the deformation and stress of the loaded tooth. For the restored tooth there is a sudden change in stiffness, resulting in stress concentrations that may cause an undesirable break of the loaded tooth. Determination of stress and strain on the physiological and saved tooth is a problem due to the complex geometry, material

* Ing. J. Valášek, Ing. P. Marcián, Ing. K. Řehák, Ing. D. Krpalek, Ing. Z. Florian, CSc., Brno University of Technology, Facuty of Mechanical Engineering, Institute of Solid Mechanics, Mechatronics and Biomechanics, FME VUT Brno, Technická 2, 616 69, Brno, Czech Republic

properties, location, and last but not least, the boundary condition of the tooth. This problem can be effectively solved by computational modelling.

2. Material and methods

For solving this problem the finite element method (FEM) was chosen and the FEM software ANSYS was used. To obtain the computational model it is necessary to create sub-models. These are a model of geometry, a model of materials, and a model of loads and boundary conditions, which clearly define the object in space.

2.1. Basic terminology of tooth anatomy and tooth cavity

A basic anatomical terminology, which describes a molar tooth (Fig.1) and cavity of second class (Fig.2) were included in this chapter for easier orientation in the solved problem. The cavity usually begins in a point (wall) of contact, in its close proximity or in the gingival third of the aproximal surface of molars and premolars [4]. This terminology is used in the analysis.

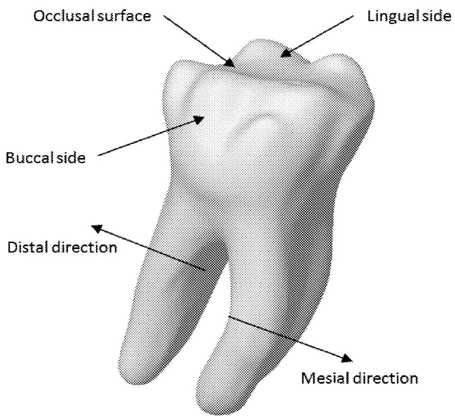

Fig.1: Anatomy of the tooth

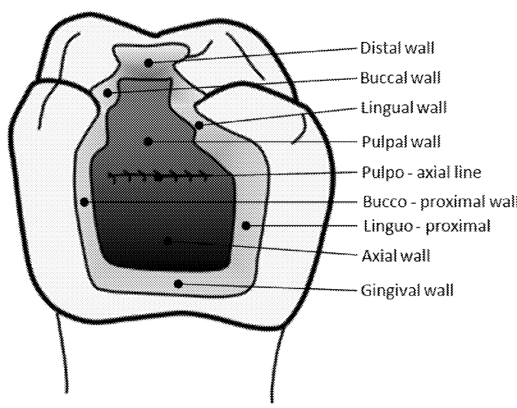

Fig.2: Description of the tooth cavity class II

2.2. Model of geometry

Models of geometry, which occur in biomechanics, have a generally complex shape which can be created by using technologies and methods of Reverse Engineering. The real object was scanned by 3D scanner and in this case the photometric sensing system ATOS II was used. The scanning takes in several directions from different angles. Cloud of points or a polygonal net are saved into the computer in the format ∗.STL. It is possible to create a model using scans obtained by computer tomography (CT). It can be reached by using image processing methods and segmentation of the cloud of points as by using STL Model Creator software [5]. The disadvantage of computer tomography is relatively low CT scans resolution. For a more accurate shape and more detailed tooth shape study it is convenient to use data from micro – CT [6]. The model of the solved tooth geometry was obtained based on the first approach using a 3D scanner. The resulting STL model was processed in the SolidWorks and CATIA programmes, where the volume model was created. The real tooth consists of several layers and each of them has different mechanical properties. The upper layer is dental enamel, which is the toughest and contemporarily the most resistant tissue in the human body. The enamel covers the whole crown (if it is not in a pathological state) and it fits tightly over another tooth layer – dentin. That makes up the main tooth part and it is harder than the bone. The tooth consists of several other layers (pulp, tooth cement, nerves, and vessel). The layers of enamel and dentin were considered for this problem as essential due to the mutual interaction between the tooth and the tooth filling. The restored tooth was considered with the second cavity class, division by Black [7], which is found mostly on teeth in the molar segment. It is necessary to prepare this cavity if a dental caries affects the interdental wall and starts opening on to the occlusal surface (bite surface). In this paper three sizes of tooth caries were considered (Fig. 3). Three different shapes of tooth cavity which simulate different retention of tooth filling, were modelled in this work (Fig. 4). The whole model of geometry was created with cortical and cancellous bone tissues (Fig. 5 and Fig. 6).

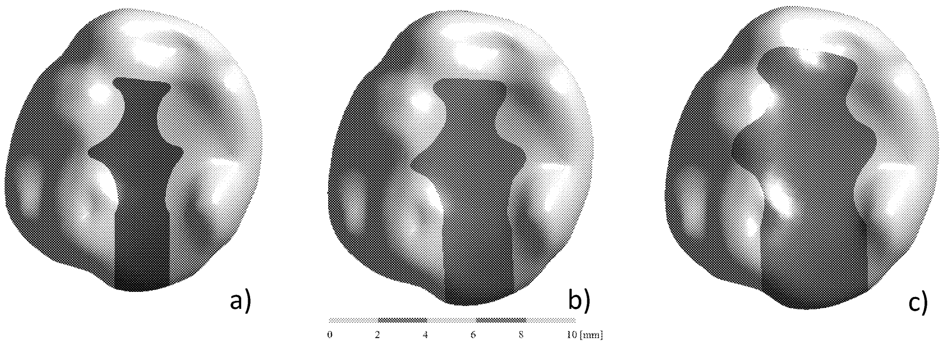

Fig.3: Different cavity size: a) minimal cavity size 1, b) middle cavity size 2, c) maximum cavity size

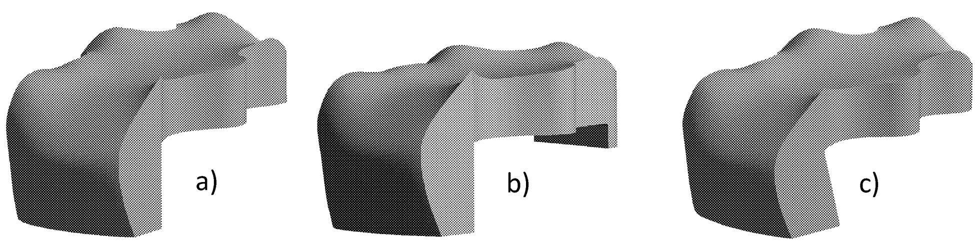

Fig.4: Different cavity shape: a) cavity shape A, b) cavity shape B, c) cavity shape C

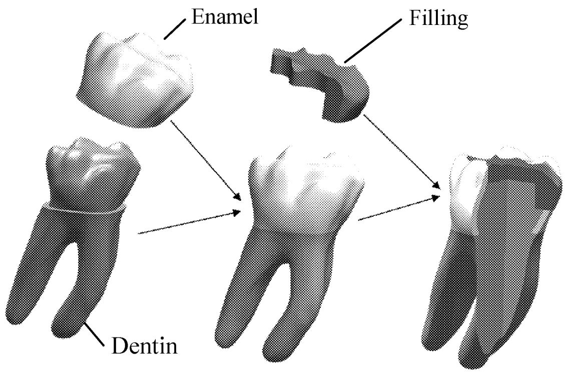

Fig.5: Dentin, enamel and filling

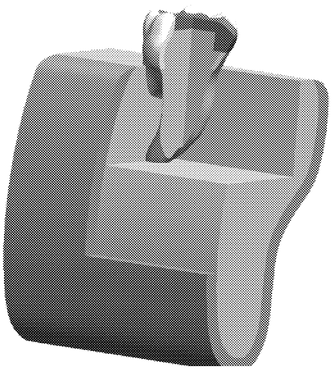

Fig.6: Whole geometry of the solved system

2.3. Model of material

In the solved systems that occur in biomechanics, there is often an interaction between living tissues and technical materials. The material characteristics determination of technical materials is easier than of biological and living tissues, which can change mechanical properties throughout their life and during an experiment. In terms of the level of the solved problem, the appropriate and validated model of mechanical properties is a homogenous, isotropic and linearly elastic model, which is explicitly described by two material characteristics: Young's modulus E [MPa] and Poisson's ratio μ [–]. Amalgams, composites resins and glass-ionomer cements are used as a filling materials at these days [8]. The first and second filling materials are convenient for a tooth restored in the molar section. The living tissue material models were based on a search study [9], [10]. Another way to obtain the material properties of a living tissue is to perform a CT scan analysis, by which it is possible to determine Hounsfield units (HU) from which the apparent density can be determined. On the basis of the apparent density the value of Young's modulus E [MPa] can be estimated [11]. The material properties used in this work are written in table 1.

Model of material	E [MPa]	μ [–]	Literature
Enamel	80 000	0.3	[9]
Dentin	20 000	0.3	[9]
Cortical bone	13 700	0.3	[10]
Cancellous bone	1 370	0.3	[10]
Amalgam	15 870	0.3	[8]
Composite resin	6 260	0.3	[8]

Tab.1. Material properties for the solved system

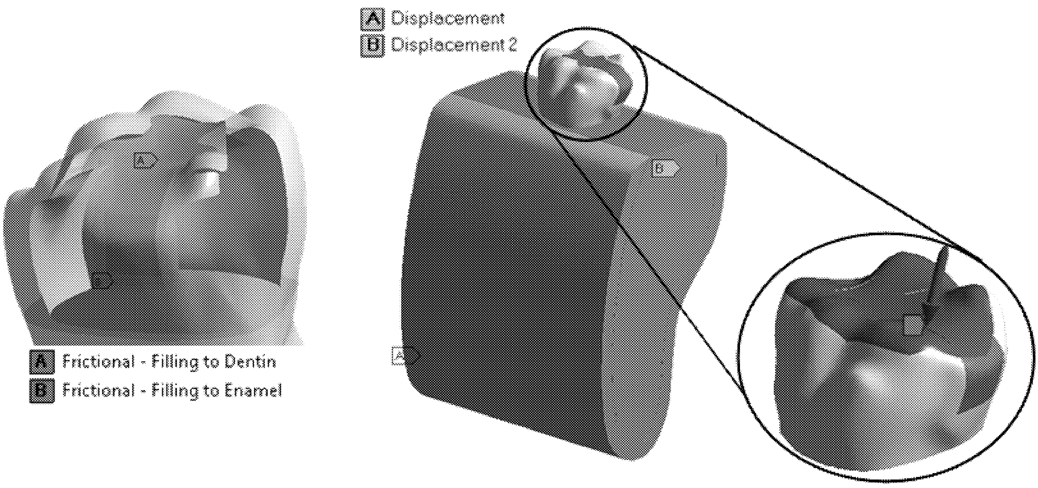

Fig.7: Contact between filling and tooth tissue; boundary conditions and loads of the solved system

2.4. Model of loads and boundary conditions

Chewing is a repeating process, by which food is chewed up and teeth are exposed to external force. The chewing force is caused by mandible and maxilla muscle activities. The chewing force size is different in individual mandible sections. The force has the biggest effect on the teeth in the molar section. The chewing force size changes depending on sex and age. The tooth is loaded by chewing in a general direction in the occlusal plane. The chewing force 200 N was chosen based on literature study [12]. The same load was used for all solved cases (Fig. 7).

It is necessary to clearly define the computational model in space. This is achieved by prescribing the boundary conditions, which prevent displacements and rotations of cortical and cancellous bone on the edge of the solved segment. A connection to the interface of the living tissue is modelled as a solid connection (the finite element mesh has the same nodes). This connection simulates the real situation, when the tissues are grown together (it is the case of the Bonded contact type in ANSYS). Dental filling is defined towards dental tissues (enamel, dentin) by using Friction contact with a friction coefficient of 0.5 .

2.5. Finite element model

To create a computational model for a computational solution by means of the finite element method, it is necessary to respect the rules and the boundary conditions of the system. In our case, it is the ANSYS 11 system. A finite element mesh was created by hexahedral and tetrahedral elements with quadratic approximation (SOLID 186 and SOLID 187). Elements TARGE 170 and CONTA 174 were used for contact pair. All elements are standard as defined in the ANSYS program. The total number of elements is similar for all solved variants and it is 250 000 elements (Fig. 8).

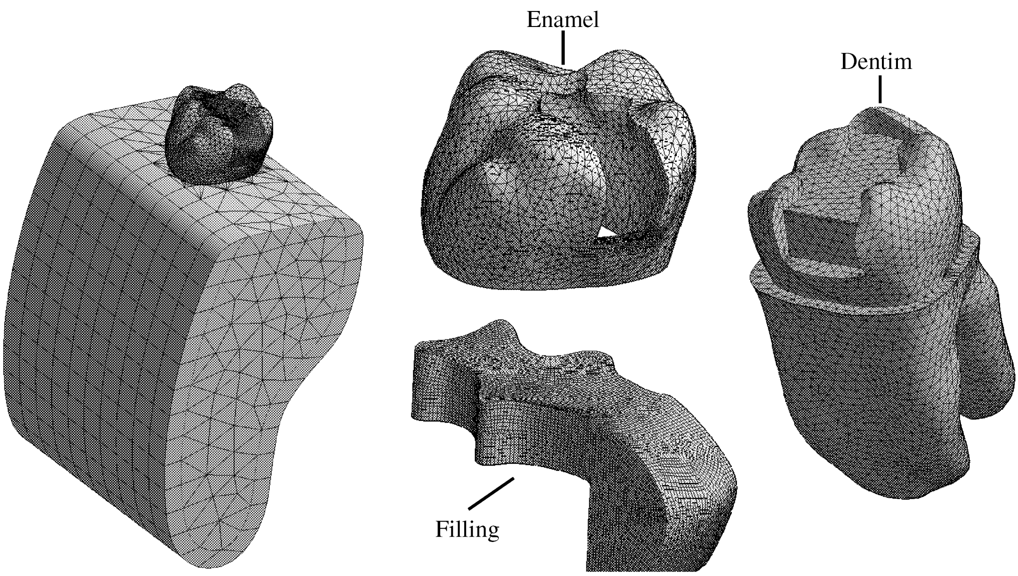

Fig.8: Finite element model of the solved system

3. Results

The eighteen variants of the computational model were created for the evaluation of the mechanical interaction between filling material and bone tissue, primarily enamel. Individual variants differ in the size of dental caries and in the different execution of tooth cavity shape. Two filling materials were considered for tooth restoration. Finite element analysis was performed for the healthy tooth model. The tooth enamel is most influenced by restoration and for this reason the enamel layer was especially analyzed. For the interpretation of stress and strain on the restored tooth it is necessary to make a comparison with these waveforms in a healthy tooth. For this reason it was convenient to perform finite element analysis on a healthy tooth.

3.1. Finite element analysis of healthy tooth

Figure 9 shows the total displacement of a healthy tooth. The biggest value of total displacement is at the mesiolingual bump. The tooth has a tendency to rotate in a lingual direction at bite and concurrently it is pressed into the mandible segment. In figures 10 a) and b) we can see the progress of the first and third principal stress (σ_1 and σ_3) on the enamel. During chewing, tooth bumps are loaded by pressure, which ranges from 4.5 MPa to 5.4 MPa. Due to the difference between the displacement of dental bumps on the lingual and buccal sides the tensile stress emerges on the circumference of the dental enamel in a range from 3 MPa to 6 MPa. On a buccal wall the tensile stress reaches 2 MPa. The area between the first and the second buccal bumps represents an exception, where the value reaches a tensile stress 5 MPa. The maximum value σ_1 is located in the middle of the tooth crown on the mesial wall and it reaches a value of 7.7 MPa. Along the whole circumference of the enamel σ_3 is close to zero MPa. The figures 10 c) and d) shows pressure on the dentin occlusal face. Pressure reaches values from 1 MPa to 2.5 MPa. The tensile stress creation on the dentin is the same as on enamel and the progress of principal stresses σ_1 and σ_3 are similar as well. Principal stresses reach lower values in these places, the range is from 0.3 MPa to 1.2 MPa.

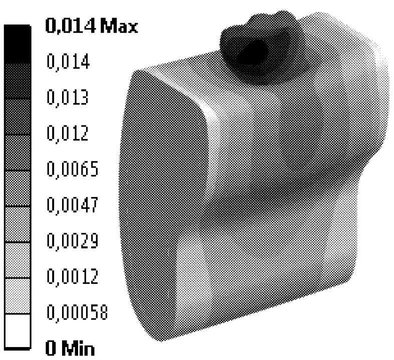

Fig.9: Displacement of the solved system [mm]

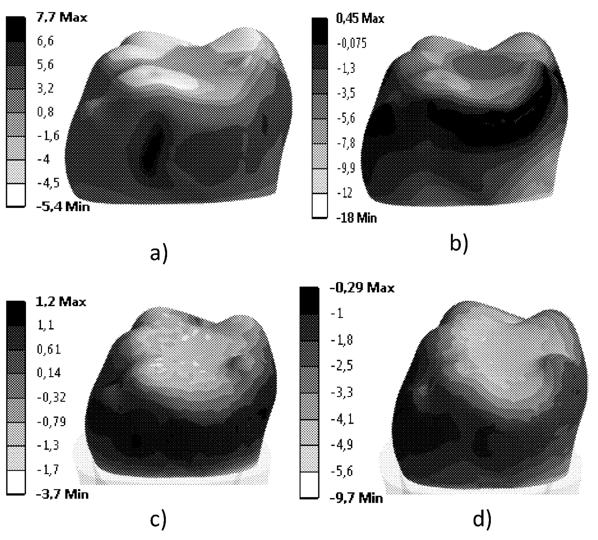

Fig.10: a) Maximum Principal Stress of enamel, b) Minimum Principal Stress of enamel, c) Maximum Principal Stress of dentin, d) Minimum Principal Stress of dentin

3.2. Finite element analysis of restored tooth

For a restored tooth 18 variants were created. The individual variants differ in their cavity size, the shape of the cavity and filling and the type of material for the filling. In the following text the effects of the individual parameters are analysed, such as cavity size, cavity shape and filling material.

3.2.1. Influence of cavity size

The first analysis are performed for effects of dental caries size. The stress concentrators are artificially made in dental enamel by restoration and there are crossings between the buccoproximal, linguoproximal and gingival walls. The tensile stresses, which cause gingival wall load, are shown in the Figure 11. They are located on the crossing of the cavity walls. Mutual approaching of cavity walls is performed and thus additional tensile stress is added. Maximum values of principal stresses $\sigma_1 = 55\,\mathrm{MPa}$ and $\sigma_3 = 8.8\,\mathrm{MPa}$ are located on the crossing of the walls, which are mentioned above. The highest values of principal stresses are in the case of the smallest cavity (size 1). The analysis of the cavity size effect shows

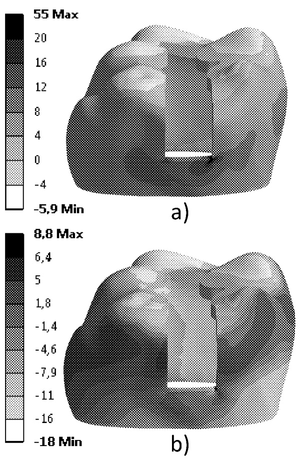

Fig.11: a) Maximum and b) Minimum Principal Stress for enamel

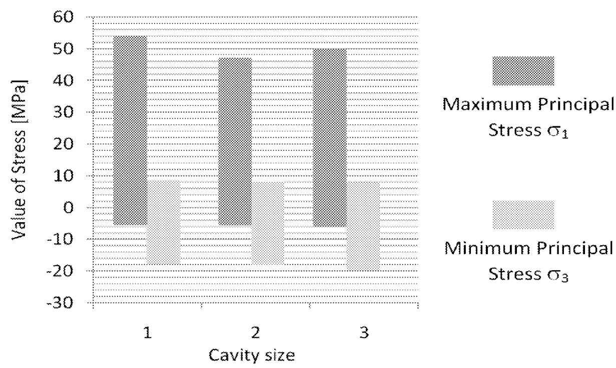

Fig.12: Graph of the stresses for enamel of different cavity sizes

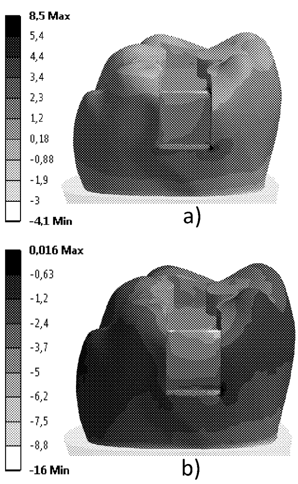

Fig.13: a) Maximum and b) Minimum Principal Stress for dentim

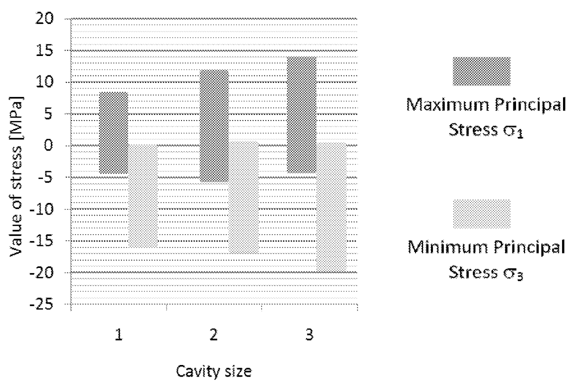

Fig.14: Graph of the stresses for dentim of different cavity sizes

that chewing force, which is transmitted over the filling, is applied on a smaller gingival wall and this situation causes higher stress on this wall at cavity size 1. The values of the principal stress in enamel are lower with the increasing cavity size (Fig. 12). The pulpoaxial edge, which is a crossing between the pulp and axial walls at dentin, is primarily loaded during chewing (Fig. 13 and Fig. 14). The amalgam filling and cavity shape A were chosen for the analysis.

3.2.2. Influence of the cavity shape

Three shapes of tooth cavity were considered for restoration. The individual shapes represent a design of filling retention primarily in dentin. The individual dental cavity shapes can be specially designed for the particular types of used filling material and specific way of anchoring. The first and third isolines of principal stresses in cavity type B are plotted in Figure 15, where the auxiliary cavity is created on the tooth occlusal surface. In addition, the principal stresses are plotted for filling and dentin. During biting a widening of the filling between pulp surface and axial wall occurs. The additional cavity helps by anchoring towards displacement in the mesial direction. As in the 3.2.1 analysis the dentin is primarily loaded on the pulpoaxial edge. The cavity size 1 with applied amalgam filling was chosen for this analysis. The pulpoaxial edge is observed location at filling and dentin.

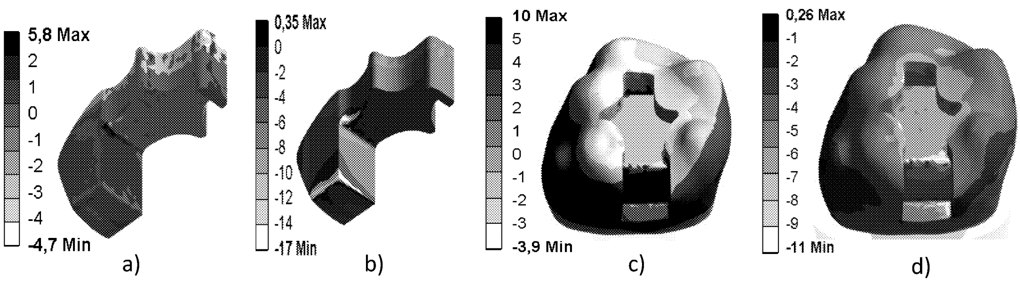

Fig.15: a) Maximum Principal Stress of filling, b) Minimum Principal Stress of filling, c) Maximum Principal Stress of dentin, d) Minimum Principal Stress of dentin – with cavity shape B

Principal stress	Cavity shape		
	A	*B*	*C*
Maximum principal stress σ_1 – filling	Max = 7.4 [MPa] Min = −3.0 [MPa]	Max = 5.8 [MPa] Min = −4.1 [MPa]	Max = 7.5 [MPa] Min = −3.3 [MPa]
Minimum principal stress σ_3 – filling	Max = 0.22 [MPa] Min = −18.0 [MPa]	Max = 0.35 [MPa] Min = −17.0 [MPa]	Max = 0.22 [MPa] Min = −20.0 [MPa]
Maximum principal stress σ_1 – enamel	Max = 55.0 [MPa] Min = −5.3 [MPa]	Max = 50.0 [MPa] Min = −5.4 [MPa]	Max = 60.0 [MPa] Min = −5.5 [MPa]
Minimum principal stress σ_3 – enamel	Max = 9.6 [MPa] Min = −21.0 [MPa]	Max = 9.6 [MPa] Min = −19 [MPa]	Max = 10 [MPa] Min = −22 [MPa]
Maximum principal stress σ_1 – dentin	Max = 11.0 [MPa] Min = −5.6 [MPa]	Max = 10.0 [MPa] Min = −3.9 [MPa]	Max = 16.0 [MPa] Min = −4.1 [MPa]
Minimum principal stress σ_3 – dentin	Max = 0.07 [MPa] Min = −21.0 [MPa]	Max = 0.26 [MPa] Min = −11.0 [MPa]	Max = 0.5 [MPa] Min = −14.0 [MPa]

Tab.2: Value of Maximum and Minimum Principal Stress for tooth tissue and filling of different cavity shapes

The principal stresses values are written in Table 2. From the table it is clear that cavity shape influences the distribution of stress and strain not only in fillings but also in dental enamel and dentin. From performed analysis it is evident, if the auxiliary cavity is created in the occlusal surface of the cavity (cavity shape B), there are principal stresses partition between the auxiliary cavity and the pulpoaxial edge. It is possible to observe similar stress and strain behaviour at the enamel and dentin. At the enamel the stress concentrator is located at the crossing of the buccoproximal, linguoproximal and gingival walls.

3.2.3. Influence of the filling material

Restoration causes a significant breach of compactness of the restored tooth and creates artificial concentrators in these dental tissues. The newly vacant place (cavity) is necessary to be filled with appropriate filling material. In this work two types of filling material are considered and they are the amalgam and the composite resin. An analysis was performed for cavity size 1 and for cavity shape C. The values of principal stresses are plotted in Figure 16.

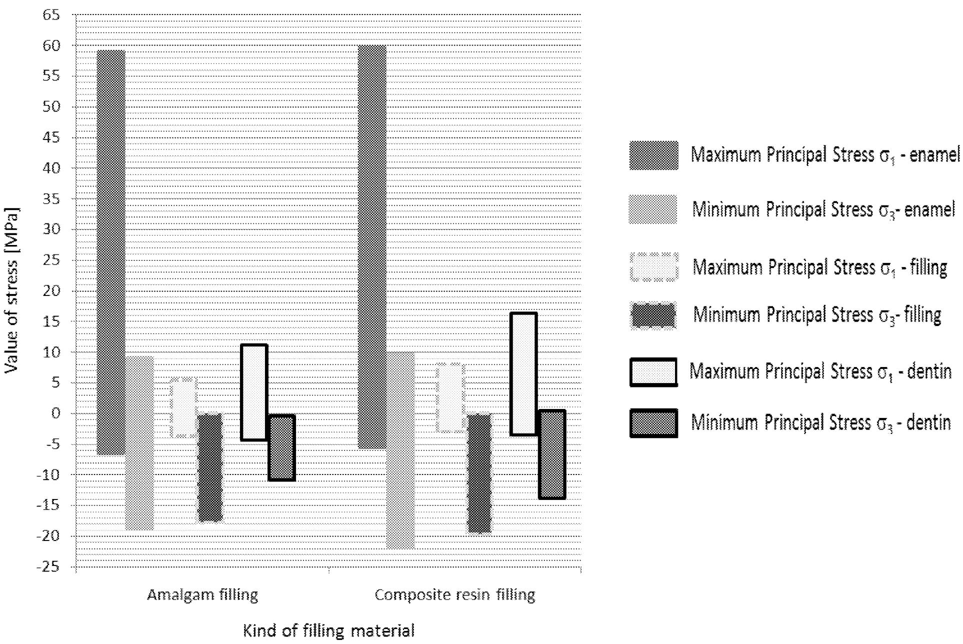

Fig.16: Comparison of maximum and minimum stress for restored tooth

The next analysis was focused on the influence of dental filling materials on the distribution of stress and strain in the dental tissue. For both filling materials the maximum and minimum principal stresses were observed for the enamel, dentin and filling. The resulting values were plotted in Figure 16. The figure shows that in the case when the amalgam is used as a filling material for the specific cavity class, the values of principal stresses are the lowest. For other filling materials the values of principal stresses increase. The differences between the values of principal stresses are in the order of percentage for dental tissues and fillings. A similar behaviour of principal stresses is possible to observe also for other sizes and shapes of cavities. The increase of principal stresses values in the dentin and filling is due to a change of filling materials. This behaviour is caused by that the amalgam has similar material characteristic to dentin ($E_{\mathrm{amalgam}} = 15\,780\,\mathrm{MPa}$, $E_{\mathrm{dentin}} = 20\,000\,\mathrm{MPa}$).

4. Conclusions

This paper is focused on stress strain analysis of the healthy and restored tooth. The performed analysis shows that principal stress σ_1 is deployed all over the healthy tooth enamel. It means that principal stress is on the lingual, buccal, distal and mesial walls. The maximum value of principal stress σ_1 is on the mesial wall of the enamel and its value is 7.7 MPa. The principal stress σ_3 is mostly of a pressure character and it reaches a value of 18 MPa on the lingual side in a location where an edge of the tooth crown pushes on the edge of the dentin. This is under the assumption that stiffness is reduced by the influence of the violation of coherence in enamel and dentin. For a restored tooth with a class II cavity principal stresses on the enamel move to the transitions between the gingival wall and the walls perpendicular to it. In these places, the principal stress σ_1 reaches a value of nearly 60 MPa and σ_3 of nearly 10 MPa for both filling materials with cavity shape C. The cavity shape influences the distribution of stress and strain as well. Values of principal stresses are lowest when using a dental cavity with auxiliary cavity (shape B). The size of the cavity is also a significant factor, which influences the principal stresses. Values of principal stresses on the gingival wall for tooth enamel are biggest due to rebuttal of this wall for the lowest cavity size (size 1). On the other hand, when the cavity size is too large (size 3) the outline of the cavity can reach locations between the bumps of dental enamel on the occlusal surface where the rupture threaten. For the reasons of large chewing forces it is suitable to use amalgam as a filling material for a tooth in the molar section. The Young's modulus of the amalgam is similar to Young's modulus of dentin and for well – executed amalgam restoration the restored dentin behaves as a single body.

Acknowledgement

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References

[1] Borák L.: Biomechanical Study of Disk Implants Part I, Engineering Mechanics, Vol. 17 (2010), No. 1, pp. 49–60, ISSN 1802-1484
[2] Marcián P.: Biomechanical Study of Disk Implants Part II, Engineering Mechanics, Vol.17 (2010), No. 2, pp. 111–121, ISSN 1802-1484
[3] Fontana M.: Defining Dental Caries for 2010 and Beyond, Dental Clinics of North America, Vol. 54 (2010), Issue 3, pp. 423–440, ISSN 0011-8532
[4] Klepáček I., Mazánek J.: Klinická anatomie ve stomatologii, Grada Publishing a.s., Aviceum, Praha 7, 2001, ISBN 80-7169-770-2
[5] Konečný O., Marcián P., Borák L., Valášek J., Krpalek D., Florian Z.: STL Model Creator, 2010, http://biomechanika.fme.vutbr.cz
[6] Marcián P., Konečný O.: On the level of computational models in biomechanics depending on gained data from CT/MRI and micro-CT, MENDEL 2011, ISSN 1803-3814, BUT FME Brno, 2011, (in press)
[7] Hellwing E., Klimek J., Attin T.: Záchovná stomatologie a parodontologie, Grada Publishing a.s., Aviceum, Praha, 2003, ISBN 80-247-0311-4
[8] Beatty M.W.: Elastic and fracture properties of dental direct filling materials, Biomaterials, Vol. 14 (1933), Issue 13, pp. 999–1002, ISSN 0142-9612

[9] Gei M.: An inter-face model for the periodontal ligament, Journal of Biomechanical Engineering, Vol. 124 (2002), No. 5, pp. 538–546, ISSN 0148-0731
[10] Carter D.: Mechanical properties and composition of cortical bone, Clinical Orthopeadics and Related Research, Vol. 135 (1978), pp. 733–741
[11] Valášek J.,Marcián P.: Material Properties of Bone Tissue Obtained from CT for Biomechanics Purposes, MENDEL 2010, pp. 483–490, ISSN 1803-3814, BUT FME Brno, 2010
[12] Curtis D.A.: Modeling of jaw biomechanics in the reconstructed mandibulectomy patient, The Journal of Prosthetic Dentistry, Vol. 81 (1999), Issue 2, pp. 167–173, ISSN 0022-3913

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