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BIOMECHANICAL EVALUATION OF STRESS-STRAIN CONDITION OF RESTORATIVE CERAMIC PIN STRUCTURES AND DENTAL ROOTS

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ABSTRACT — The authors have proposed a ceramic stump pin inlay featuring a ceramic coating of the over-the-root part, which acts as a covering aesthetic design, as well as strengthens the stump retention, distributes rationally the functional load and strengthens the resulting system. This work offers a view at the outcomes of studying the stress and strain status of the proposed design for a ceramic stump pin inlay through the method of finite elements on a three-dimensional mathematical model. The designed 3D mathematical model included, as initial data, the specific features of the cortical bone, the cobalt-chrome alloy, the facing field-spathic ceramics, and tooth dentin. We studied the distribution of stresses occurring while employing the specially designed pin structure under the effect of multidirectional loads of 150 N, directed strictly down relative to the tooth longitudinal axis (vertically), and the load at a 45° angle. The proposed newly designed inlay allows reducing the maximum stress within the ceramic coating by 51.8% at a vertical load, and by 43.2% at a side load of 45°, compared to traditional metal-ceramic structures.

KEYWORDS — stump pin inlay, tooth root, metal & ceramics cap, stress and strain status.

INTRODUCTION

There is a wide range of ways to restore severely damaged tooth crowns [5, 8] available nowadays. The leading position among the prosthetics methods used for this pathology belongs to pin structures, namely stump pin inlays covered with artificial crowns, as well as pin teeth. The successful outcome of orthopedic treatment will ultimately depend on the manufacturing technology and the pin structure design [2, 6, 7].

In order to detect the stress-and-strain status of complex geometric objects, only the finite element method will make the best choice [1, 3, 4]. Mathematical modeling allows displaying and forecasting am enormous number of geometry behaviors as well as predict the future of the object of study, with no real experiment (https://www.ansys.com/solutions/solutions-by-industry/healthcare).

Through our work, we used the ANSYS Academic Research Release 2020K1 software package (academic license for scientific research), which includes modules for geometric modeling ANSYS Space Claim, ANSYS mechanical strength problems solutions, whereas professional advice was offered by Kondratev D. V., an expert of the CADFEM-CIS company (Samara, Russia).

The Aim of this study

is to evaluate biomechanical effectiveness of the proposed ceramic pin structure using the finite element method on the designed 3D mathematical model with multidirectional loads.

MATERIALS AND METHODS

Two detailed mathematical models were developed to solve the tasks (Fig. 1). These two objects were used to model the same dimensions (root length and canal diameter, size of the pin part, etc.). The models were divided into 2 groups depending on the studied pin structure.

Group 1 studied the stress-and-strain status of the traditional method for restoring a missing clinical tooth crown.

The method implied the following: a stump pin was made of a cobalt-chrome alloy (CCA) for the tooth root, which was fixed in the root canal with cement (GC Fuji I). Further, a metal & ceramic crown was made, which, too, was fixed on the stump pin inlay with cement (GC Fuji I) (Figure 1a).

Group 2 included a model that studied the stress-and-strain status of the proposed pin structure (Federal Institute for Industrial Property, Decision to grant a patent of the Russian Federation under application 2019143931 dated 23/12/2019).

The point of this design was as follows. A pin tooth was made for the tooth root (a stump pin inlay with ceramics applied to it by firing), which was fixed in the tooth root canal by cement (GC Fuji I). The crown part attachment angle to the tooth root was 90 degrees. During that, the pin tooth specific design feature is that the ceramics contacts the tooth supraradicular surface (Fig. 1b).

The geometric models were broken up by a finite element grid consisting of tetrahedral elements. The area of our interest — the crown and the pin were broken by elements with face sizes up to 0.1–0.2 mm, the rest of the model size — up to 0.4 mm (Fig. 2).

To calculate the stress-strain status, we used the data on the components of mathematical models (dentin, CCA, ceramics, etc.), as is shown in Table 1.

The strength analysis of the above models was performed with two loading options. Next, we will call these Step 1 and Step 2. At Step 1, a compressive load of 150 N with a constant intensity was applied to the crown part of the device, directed strictly downward relative to the tooth longitudinal axis (vertically) — Fig. 3a. At Step 2, a 150 N load of constant intensity was again applied at an angle of 45° relative to the tooth longitudinal axis — Fig. 3b. The model was fixed on the end-side surfaces, where the stresses were not taken into account. The study area was located at a distance of more than 5 typical dimensions (the tooth crown height) from the fixing point.

The models were analyzed regarding the stress distribution in ceramics, in the metal part of the pin structure, and in the tooth root. Given that the analyzed materials have different properties, several stress options were employed to evaluate the stress status. The first is the equivalent Mises stress (recommended for viscous bodies, such as metals — the greatest energy theory) and the maximum principal stress (recommended for brittle solids, such as ceramics or bone — the greatest stress theory).

For a more detailed understanding, the data for the resulting stresses was obtained separately in the ceramics, in the pin-stump part and in the tooth root.

RESEARCH OUTCOMES

Results of the stress & strain status in Group 1.

Figure 4 below shows the results of equivalent stresses in the metal & ceramics crown (Group 1) with a vertical load and a load applied at an angle of 45°. Fig. 5 shows the maximum main stresses in the ceramic coating.

The results of studying the stress & strain status of the experimental mathematical model in Group 1 showed that the maximum stress area under vertical load is the contact spot between the crown and the tooth root (Fig. 4a). When the angle of application of the functional load relative to the occlusal surface of the tooth crown changes within 45°, the stresses change towards increase (Fig. 4b). The most dangerous for the ceramic coating are the tensile stresses that occurred at a side load of 174 MPa (Fig. 5b). The tensile strength value is exceeded at Step 2 (the tensile strength of ceramics is 48 MPa). In case of a vertical load (Step 1), the maximum stresses were recorded within 14 MPa, which confirms a sufficient strength margin of the ceramic coating under this loading option (Fig. 5a).

Fig. 6 shows the equivalent stresses that occur in a cast stump pin inlay. The same goes about Steps 1 and 2.

Fig. 6 shows that the stress distribution pattern corresponds to the stress distribution pattern typical of cast metal pin structures. The major changes manifested as high stresses (MPa) were observed at a side load of 150N (Fig. 6b). In this case, the strength limit for the cast pin inlay was not exceeded (the compressive strength of the CCA is 450 MPa, the tensile strength is 655 MPa), which means there is still a safety margin remaining.

Fig. 7 shows the results of equivalent stresses in the tooth root (Group 1) with a vertical load and a load applied at an angle of 45°.

Fig. 7 shows that the maximum stress area is located in the root neck part (the contact spot between the crown and the root). The most dangerous are tensile stresses at a lateral load of 89 MPa (Fig. 7b) with a dentin tensile strength of 105 MPa. The dentin under the inlay and the crown was under a strong tensile stress and thus may be subject to future destruction.

Results of the stress & strain status in Group 2.

Figure 8 below shows the results of equivalent stresses in the crown part of the pin tooth (Group 2)

Table 1. *Materials properties*

Material	Young's Module (Pa)	Poisson's Rating	Strength	
			Compressibility (MPa)	Tensile (MPa)
Cortical Bone	13.7e9	0.30	156	85
Cobalt-Chrome Alloy	225e9	0,35	450	655
Ceramics	69e9	0,28	450	48
Tooth dentin	18e9	0,31	310	105

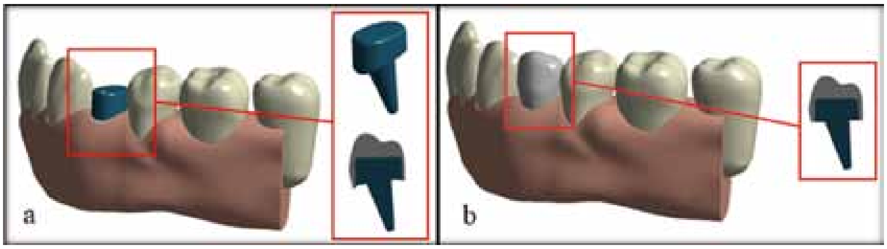

Fig. 1. Solid-state model of the lower jaw sector with a stump pin inlay installed in the tooth root: a — Group 1; b — Group 2

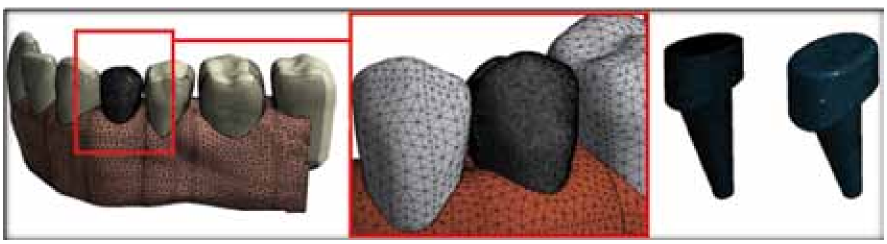

Fig. 2. Finite element model of the system

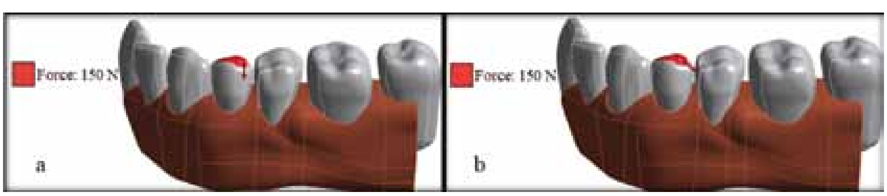

Fig. 3. Boundary conditions of the design model: a — Step 1, vertical load; b — Step 2, load at an angle of 45°

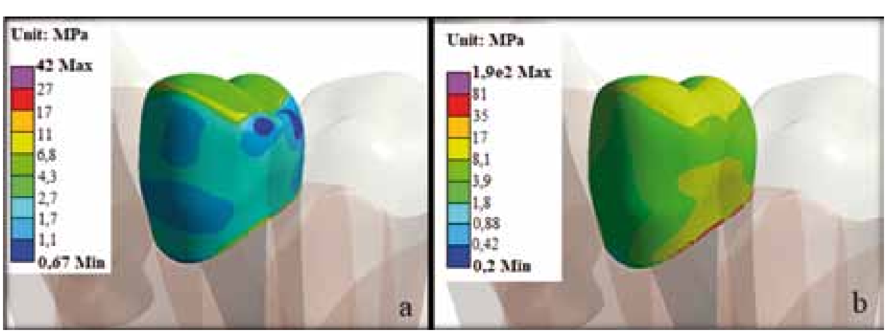

Fig. 4. Equivalent stresses in the metal & ceramics crown. Group 1: a — Step 1 (vertical load); b — Step 2 (load at an angle of 45°)

with a vertical load and a load at an angle of 45°. Fig. 9 shows the maximum major stresses in the ceramic coating of the pin tooth.

The results of studying the stress & strain status of the experimental mathematical model in Group 2 revealed that the maximum stress area under vertical load was the area of contact between the crown and the tooth root (Fig. 8a). When the functional load application angle relative to the occlusal surface of the tooth crown changes within 45°, the stresses change upwards (Fig. 8b). The most dangerous, yet not critical for the ceramic coating were the tensile stresses that occurred at a lateral load equal to 30 MPa (Fig. 9b). The tensile strength value at Step 2 was not exceeded (the tensile strength of ceramics is 48 MPa). Under a vertical load (Step 1), the maximum stresses were recorded within 6.2 MPa (Fig. 9a), which points at a significant strength margin that the ceramic coating has under this loading option.

Fig. 10 shows the equivalent stresses that occur in the cast base of the pin tooth. The same with Steps 1 and 2.

Fig. 10 shows that the stress distribution corresponds to the stress distribution pattern typical of cast metal pin structures. The main changes revealed as high stresses were identified at a side load of 77 MPa (Fig. 10b). In this case, the strength limit for

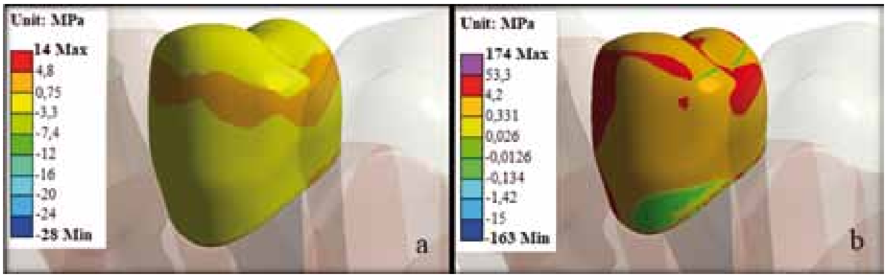

Fig. 5. The maximum principal stresses occurring in the ceramics. Group 1: a — Step 1 (vertical load); b — Step 2 (load at an angle of 45°)

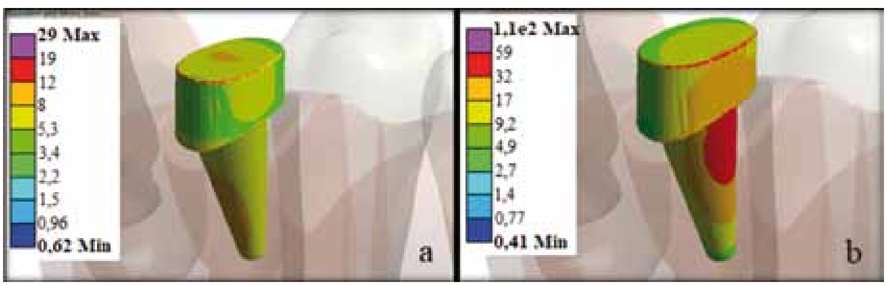

Fig. 6. Equivalent stresses in the stump pin inlay. Group 1: a — Step 1 (vertical load); b — Step 2 (load at an angle of 45°)

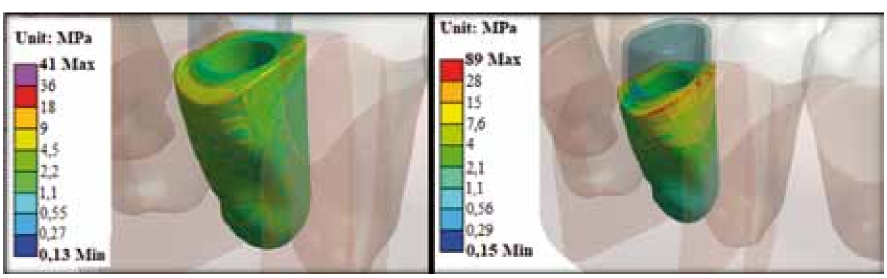

Fig. 7. Equivalent stresses in the tooth root. Group 1: a — Step 1 (vertical load); b — Step 2 (load at an angle of 45°)

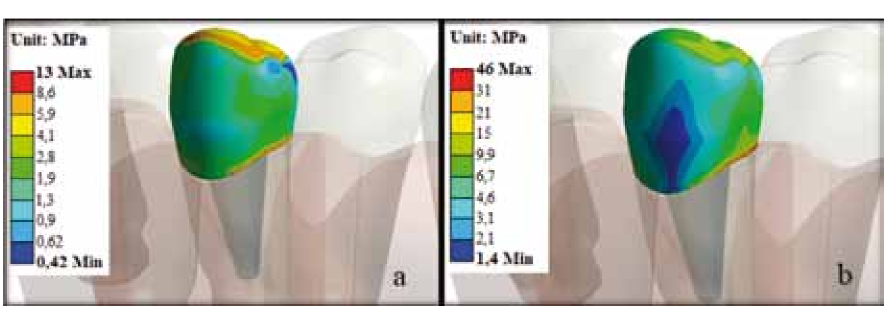

Fig. 8. Equivalent stresses in the crown part of the pin tooth. Group 2: a — Step 1 (vertical load); b — Step 2 (load at 45°angle)

the cast pin inlay was not exceeded (the compressive strength of the CCA is 450 MPa, the tensile strength being equal to 655 MPa), which points at a safety margin available.

Fig.11 shows the outcomes for equivalent stresses in the tooth root (Group 2) with a vertical load and a load at an angle of 45°.

Figure 11 offers a clear picture showing that the area of maximum stress is the neck part of the root (the contact spot between the crown part of the device and the tooth root). The most dangerous are tensile stresses at a lateral load of 29 MPa (Figure 11b) with a tensile strength of 105 MPa for dentin. The dentin of the tooth under the inlay and the crown was subjected to a slight tensile stress, which is expressed through a sufficient safety margin available.

Tables 2–4 offer a look at a comparative analysis of the obtained quantitative data for the maximum and average stresses depending on the study group as well as the part of the system.

Table 2 shows that the resulting maximum stresses registered in the pin structure's crown part were the highest in Group 1, where the traditional method was employed to manufacture the stump pin inlay followed with its further coating with a metal & ceramics crown. These indicators were the highest for both the vertical (27 MPa) and the lateral load (81 MPa). Given the

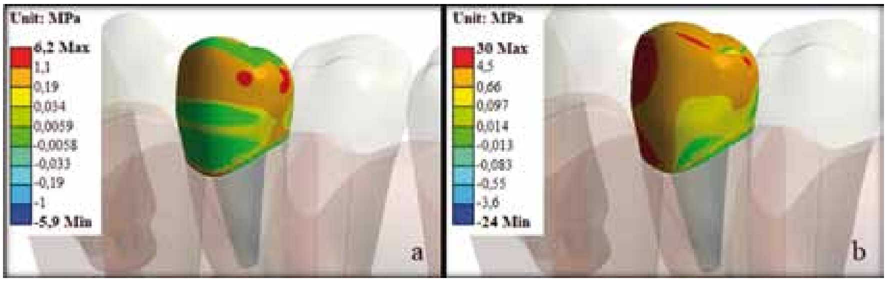

Fig. 9. The maximum major stresses occurring in the ceramics. Group 2: a — Step 1 (vertical load); b — Step 2 (load at 45°angle)

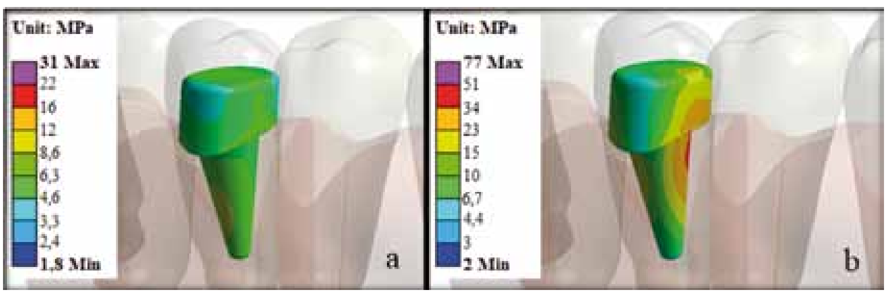

Fig. 10. Equivalent stresses in the metal base of the pin tooth in group 2: a — Step 1 (vertical load); b — Step 2 (load at an angle of 45°)

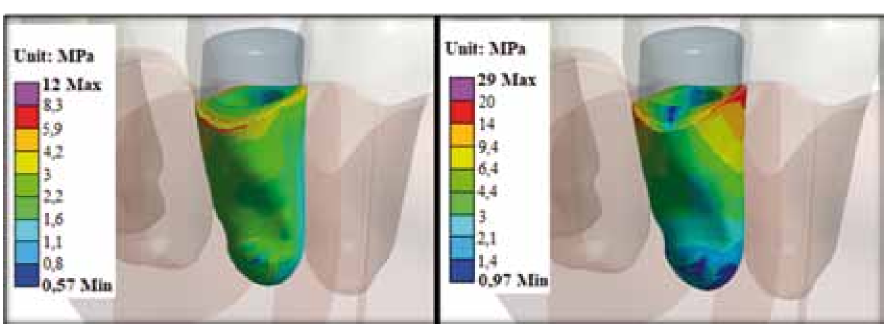

Fig. 11. Equivalent stresses in the tooth root. Group 2: a — Step 1 (vertical load); b — Step 2 (load at 45°angle)

fact that the critical stresses leading to the ceramics chipping were those at 48 MPa, we are safe saying that the ceramic coating of this type of the orthopedic structure will prove more susceptible to destruction in the future. Using the newly proposed version of the pin tooth allowed reducing the occurrence of maximum stresses in the ceramic coating. A mathematical analysis in Group 2, for instance, showed that under a vertical load this indicator decreased by 51.8% (13 MPa), while in case of a side load of 45° it went down by 43.2% (46 MPa), compared to Group 1.

The obtained results of maximum equivalent stresses in the pin structure metal base (Table 3) offered a slightly different picture rather than the ceramic coating. Under a vertical load, we found the lowest values of the maximum stresses in Group 1 (19 MPa). In Group 2, this indicator was higher by 15.7% (22 MPa). Under a side load, the maximum stresses in the cast base of the pin structure in Group 1 reached 59 MPa, whereas in Group 2 they were 51 MPa. However, given that the critical stresses leading to the CCA destruction imply 665 MPa, both groups have a huge margin of safety, this, in turn, meaning that the destruction would likely affect the fragile items (tooth root or crown part) and this element had no critical role within our system, *the crown part of the device – the pin — the tooth root*.

The results of maximum stresses occurring in the tooth root (Table 4) under a vertical load and at an angle of 45° were highest in Group 1 reaching 36 and 99 MPa, respectively. So in Group 2, the vertical and the lateral load led to the maximum stresses of 9 and 20 MPa, respectively, which is 75 and 65% below similar indices in Group 1, which indicates rather a significant load on the root, whereas when in case of bending loads, destruction of the root edge areas cannot be excluded.

CONCLUSION

In view of the above, based on the data obtained from the stress & strain status analysis for three-dimensional mathematical models of destroyed teeth restored through various types of stump pin structures, the following conclusions can be made:

Table 2. *Results of maximum stresses in the crown part of the pin structure*

Group	Maximum equivalent stresses, MPa		Critical stresses leading to ceramics chipping (MPa)
	90°	45°	
1	27	81	48
2	13	46	

Table 3. *Results of maximum stresses in the metal base of the pin structure*

Group	Maximum equivalent stresses, MPa		Critical stresses leading to CCA destruction (MPa)
	90°	45°	
1	19	59	665
2	22	51	

Table 4. *Results of maximum stresses in the tooth root*

Group	Maximum equivalent stresses, MPa		Critical stresses leading to tooth root destruction (MPa)
	90°	45°	
1	36	99	22
2	9	20	

1. The proposed ceramic stump pin inlay will not only minimize the stresses in the tooth hard tissues yet also will reduce significantly the stress & strain status on the border of the pin structure and the locking cement under various-direction loads, thus reducing the risk of decementation and broken orthopedic structure.
2. The stress distribution pattern for all the examined types of stump pin structures is in line with the nature of stress distribution typical of rigid solids with a load concentrating predominantly at the pin top. A significant stress reduction in the proposed ceramic stump pin inlay, if compared to the conventional design, is due to a significant stress reduction at the *fixing material — pin structure* border under lateral and oblique loading.
3. As the area of the greatest stress concentration in Group 1 is located in the tooth dentin at the border with the artificial crown edge and embraces a small area of maximum stress, maintaining the inlay precision in the tooth neck could be a good option.
4. The newly designed ceramic stump pin inlay allows significant reduction in the equivalent stresses not only at the area where the different materials come in contact — in the root dentin — yet also at the pin structure top with no risk of dangerous loads concentration, thus minimizing the probability of root fractures.

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