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STRENGTH ESTIMATION OF A FIXED BRIDGE PROSTHESIS

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Abstract: The original design of a fixed bridge prosthesis is suggested aiming to eliminate adentia of children up to 14-16 years. It does not prevent the growth of alveolar arc and excludes the twist of supporting teeth. Two-stage evaluation of prosthetic strength was performed using the finite element method. On the first stage the problem of contact interaction between intermediate partial elements of the prosthetic device with allowance for mobility of supporting teeth was solved. On the second stage the strength evaluation in prosthesis-tooth joining area and strength evaluation for two variants of crown construction (total and lateral) were performed.

Key words: paediatric dentistry, adentia, fixed bridge prosthesis, method of finite elements, stress analysis

Introduction

Traditionally, laminar removable dentures are used in paediatric prosthetic dentistry for eliminating of partial adentia. Their usage brings some problems: long period of habituation, need of removing and cleaning after eating and before sleeping, diction breach, irritating influence on the palate and alveolar mucosa. The fixed prostheses with the bilateral stiff fixation can be used after completion of growth of alveolar processes and jaws only: in frontal division after 16-18 years, in lateral – after 18-20 years [1,2].

Authors suggest a new design of fixed dismountable bridge prosthesis, which consists of two thin-walled half-crowns and dismountable intermediate part fastened on them. The

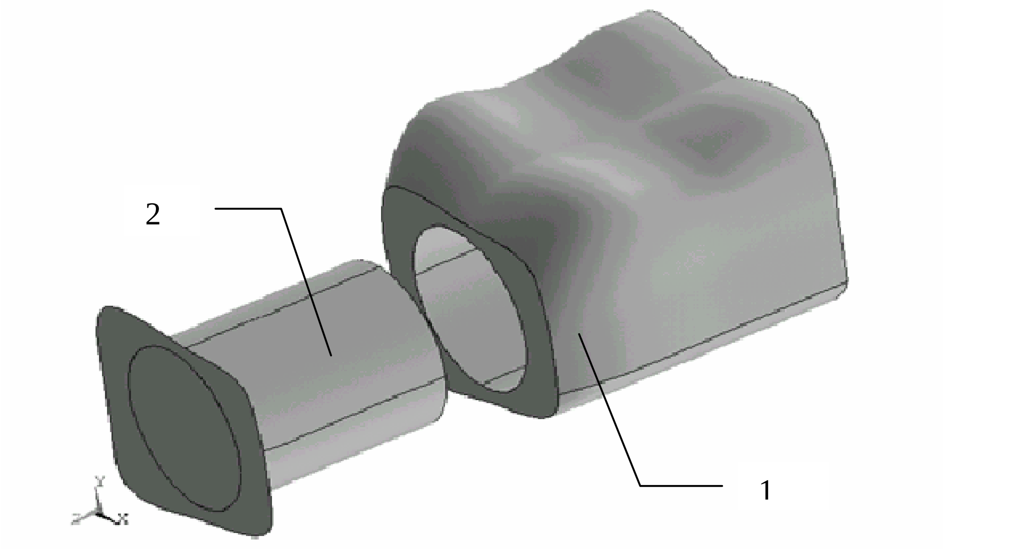

Fig.1. Intermediate part of prosthetic device in the disassembled state (contact problem).
1 - working element, 2 - directional element.

design of the prosthetic intermediate part in the disassembled state is shown in Fig.1.

The prosthetic device consists of two elements. The following terms are used for their marking hereinafter: working element – WE (1 in Fig.1); directional element – DE (2 in Fig.1). Both elements are placed between supporting teeth and are fastened on crowns (not shown in Fig. 1) by means of soldering or welding.

From vestibular side of WE a plastic facet is fixed. In longitudinal (along the alveolar arc) direction there is a cylindrical hole in WE, in which directional element is inserted with the clearance about 0.02 – 0.05 mm. The depth of hole is 2 - 3 mm less than DE length. In case of need the cavity is filled by the rubber-like material (elastic element) for making an effort to prevent approaching of supporting teeth.

The mechanical parameters of elastic element – elastic modulus E and Poisson's ratio ν – are selected so that the repulsion effort is noninvasive and does not damage the periodontium and the initial strain corresponds to assumed teeth displacement at the moment of jaw growth completion.

The given design of prosthesis does not restrain alveolar process growth, because a sprig is gradually pulled out from the channel. A certificate on the useful model №97107242/20(007941) is distributed by the Russian Research Institute of State Patent Examination. In this article, efficiency of presented model is substantiated by finite element evaluation.

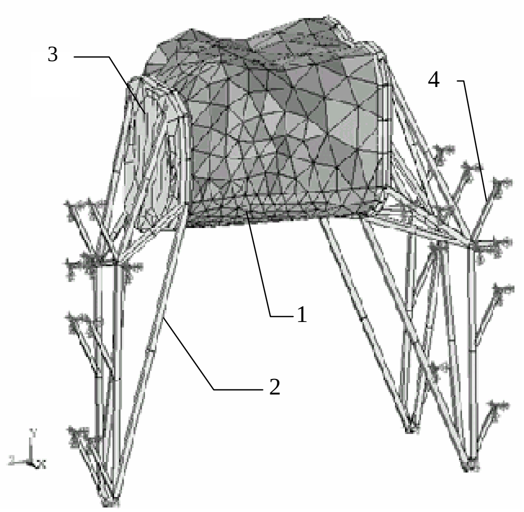

Fig. 2. The design scheme of the contact problem. Explanations are in the text.

The working element is fastened on the tooth console, by means of crown, which, in turn, is stuck to teeth surface by light-composite material. The working element leans to the directional element which results in disappearing of some part of dangerous bending stresses due to influence of the chewing pressure. But probability of exfoliation of crown from tooth under tensile stresses in working element-tooth fastening zone exists since prosthetic intermediate part is not solid.

The solution of three-dimensional non-linear contact problem is required for the strength evaluation of prosthetic device. Calculation was executed with the help of finite element method packet ANSYS (release 5.3).

The following simplifying hypotheses are assumed: material properties of living tissues, prosthetic device and crown are linear; contact of parts of prosthetic device is elastic.

Even with these assumptions the solution of this problem requires significant resource of operative memory and machine time, so evaluations were conducted in two stages:
analysis of stress redistribution in supporting teeth - intermediate part system taking into account contact interaction of working and directional elements;
elaborated evaluation of stress in zone, where working element is fastened to the supporting tooth, evaluation of construction strength.

Stage 1. Stress redistribution in supporting teeth - intermediate part system

The design scheme is shown in Fig.2. The elements of the prosthetic device intermediate part (1 in Fig.2) were considered as three-dimensional, linear-elastic objects. The prosthetic device is made of KHS titanium alloy. Mechanical characteristics KHS are determined in book [4]:

tensile strength $[\sigma_B]_{KHS}$ =600 MPa;

Young's modulus E_{KHS} =15200 MPa;

Poisson's ratio ν_{KHS} =0.28.

Supporting teeth are presented by beam structure (2 in Fig. 2). Young's modulus of a beam is 2 orders larger than Young's modulus of prosthetic device material, herewith their strains are possible to neglect. Two flat plates have similar features, through which working and directional elements are connected with supporting teeth (3 in Fig. 2). System mobility is defined by elastic properties of periodontum, which is presented by the set of rod elements (4 in Fig. 2), fastened on beams (root of tooth) by one of their ends. Their second ends are immovable. Cross-section area and elastic modulus of rods are selected so that applying of the critical pain load (150-200 N) evokes maximum vertical displacement of supporting tooth about 0.1-0.15 mm [5].

Two variants of solution are compared:
1. contact between prosthetic device elements is absent;
2. there is an elastic contact between WE and DE.

Such solution allows to estimate reduction of tensile stresses in fastening working element - tooth zone when its opposite end is leaned on DE, in contrast with situation, when such leaning is absent. The results are used in step 2 (elaborated calculation).

For discretization of the details of prosthetic device (1 in Fig. 2) three-dimensional linear four-node tetrahedral elements SOLID92 from ANSYS 5.3 were used. Connecting plates (3 in Fig.2) were divided by shell elements SHELL63.

Table 1. Elements features of the first stage problem.

Element Name	Element type	Number of nodes	Number of DOFs in node	Geometry	Number of elements
SOLID92	SOLID	10	3	Tetrahedron	3155
SHELL 63	SHELL	3-4	6	Tetragon	388
BEAM 4	BEAM	3	6	Line	95
LINK 8	LINK	2	3	Line	21
CONTAC 49	CONTACT	4-5	3	Tetrahedron	96

BEAM4 Elements (2 in Fig. 2) were used for discretization of the beam part of the construction. The periodontum was presented by LINK8 elements (4 in Fig.2). ANSYS 5.3 allows to combine different types of finite elements in one problem. Herewith all corresponding degrees of freedom for different element types in common nodes were coincidental unless additional restrictions were superimposed. Additional restrictions were not entered in given problem. Three-dimensional elements CONTAC49 were used on contact surfaces. Features of enumerating elements are shown in Table 1. Total number of degrees of freedom was 4702.

Penalty method [6] was used in ANSYS 5.3 for the contact problem solution. Special finite elements of "node-to-surface" type were created on contact surfaces. Force vectors of solid elements entered in the contact were increased proportional to depth of penetration Δu_i and prescribed contact stiffness C_{con}=0.5 E_{KHS} when the i-th node in one of contact surfaces crosses plane of finite element on another (target) surface. Iterative process was used in accordance to Newton-Raphson method [8] and finish condition

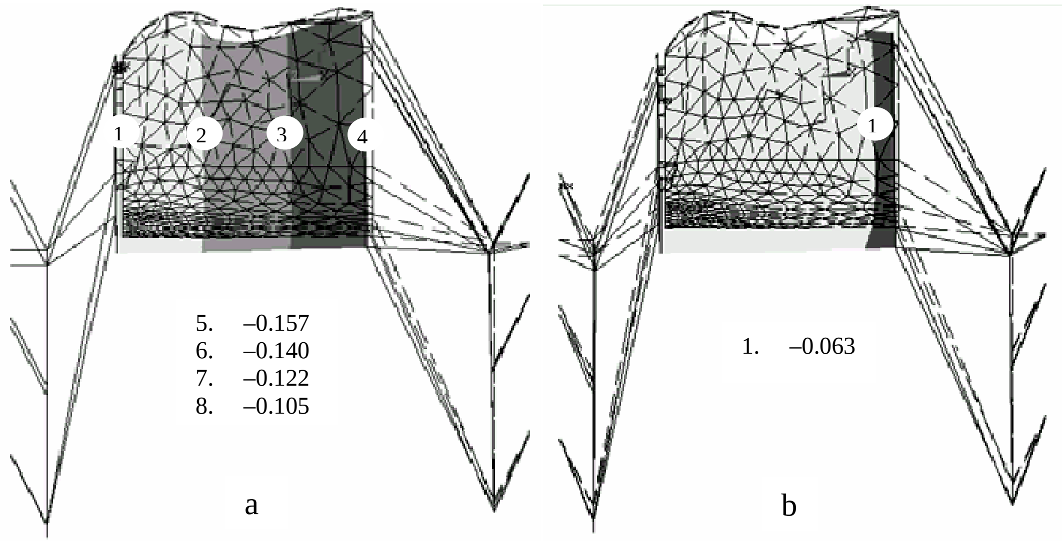

Fig. 3. Displacements in the prosthetic device, mm. a - without the contact with DE; b - with contact interactions.

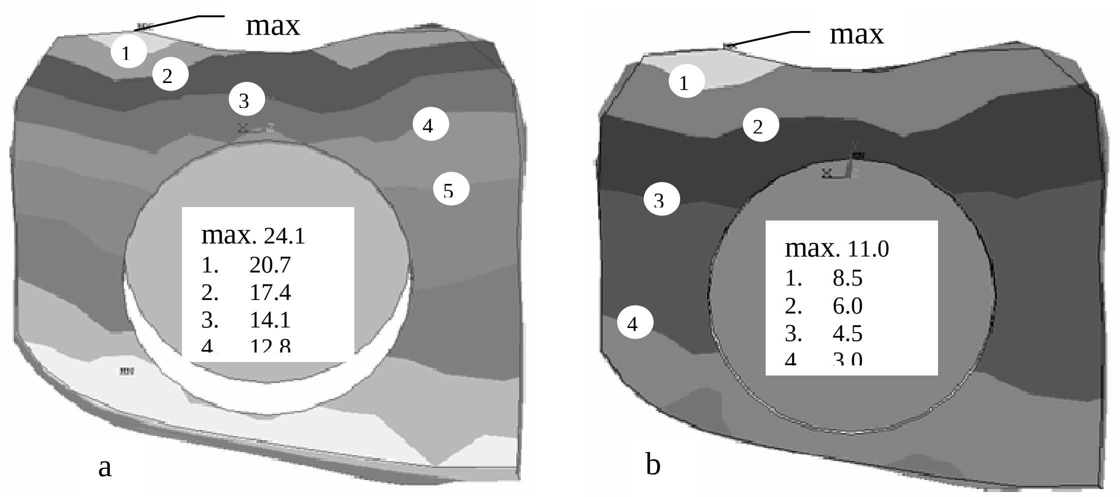

Fig. 4. Principal stress in WE-to-teeth fastening plane. Here and hereinafter stresses in MPa. a –– without support on WE; b – with support on WE.

$$\left\|\Delta\bar{u}\right\| / \sqrt{N} \le \Delta u_{cr},$$

where $\left\|\Delta\bar{u}\right\| = \sqrt{\sum_{i=1}^{N} \Delta u_i^2}$ is a cubic norm [9] of $\left\{\Delta u_1, \Delta u_2, ..., \Delta u_N\right\}$vector; N is number of contact nodes; Δu_{cr} – prescribed accuracy of calculation of penetration depth. Friction between contact surfaces was absent. Initial clearance between them is 0.02 mm. DE diameter was taken 4 mm.

A uniform distributed pressure p=3.6 MPa was applied to the active upper surface of WE. It corresponds to critical chewing force P=170 N. Pressures are not presented in Fig.2.

The results of two variants of the first stage described above are shown in Fig.3 – 5. Fig. 3a,b show the contours of loaded prosthetic device displacements. Stroken lines show shape of construction in the free state. The scale of displacements in Fig.3,a is 3:1, b – 10:1.You can

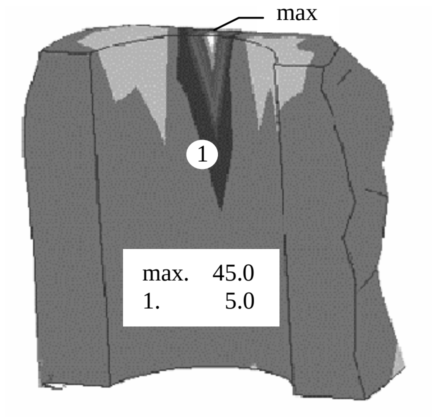

Fig. 5. Contact stresses in the working element.

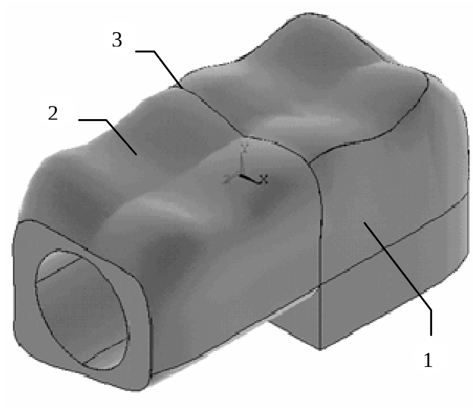

Fig. 6. WE on the tooth. 1 – tooth; 2 – working element; 3 – border of section.

see in Fig.3 that if DE support is absent, the maximum value of supporting tooth horizontal displacements u_z =0.12 mm is commensurable with vertical u_y =0.15 mm that could be the reason of its twisting in practice.

In case of WE - DE contact (Fig. 3, b), displacement u_z decreases to 0.015 mm, i.e. by 8 times, and vertical – to 0.065 mm, i.e. more than by 2 times. Thereby, the DE support practically avoids tooth twisting.

Figure 4 illustrates a distribution of principal stresses in the fastening (working element - supporting tooth) zone. Their most value for the first variant of evaluation (Fig.4, a) is close to the tensile strength limit of light-composite, used as glue $[\sigma_B]_{LC}$ =20MPa. Fig. 4,b shows that the presence of contact with DE reduces a maximum stress level in dangerous zone by 2 – 2.5 times and creates 2-times strength reserve because of the load redistribution between WE and DE through contact surfaces.

The contact stresses on upper surface of WE hole are shown in Fig.5. Area of contact is small and is located near external borders of the hole. Maximum stress is approximately 4 times less than titanium yield point $[\sigma_B]_{KHS}$, however the wear of contact surfaces and the increase of initial clearance are inevitable.

The first stage results analysis shows that absence of directing element may become a reason of failure of adhesion between WE and the tooth. DE reduces dangerous stresses by 2.5 - 3 times, hereunder enlarging strength of construction as a whole. But exact stress values in dangerous zone can not be calculated at the first stage, since supporting tooth itself is presented in model by the flat object, and crown is absent. For further revision of stress evaluation the second stage of solution was used.

Stage 2. Elaborated evaluation of stress in WE - supporting tooth system

The purpose of this stage is an analysis of influence of crown design on strength of working element-to-tooth joint. The construction is shown in Fig. 6. Tooth is presented by its higher part, still fixed on plane of "shear". Directional element is absent. Working element is a three-dimensional solid. Border between them is shown in Fig. 6 (line 3). Mechanical properties of tooth enamel [5] are:

$$E_e=4500 \text{ MPa};$$

$$\nu_e=0.36.$$

Two types of solution were used as in the stage 1:

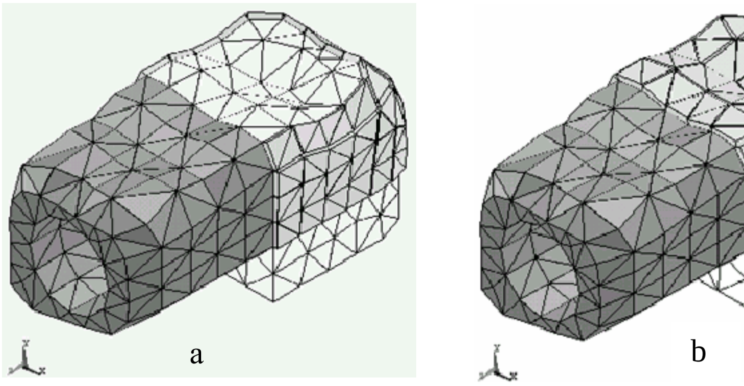

Fig. 7. Finite-element mesh of construction: a – with the lateral crown; b - with the total crown.

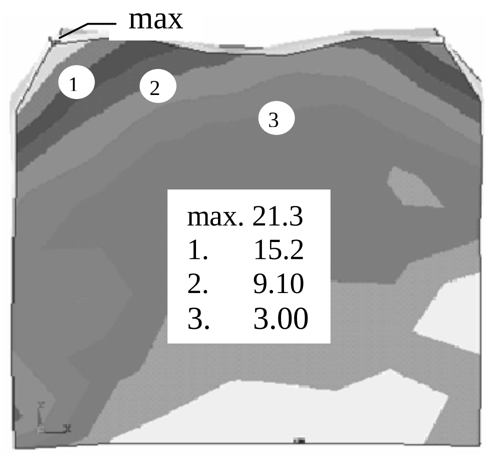

Fig. 8. Stresses in the border section. Crown is absent.

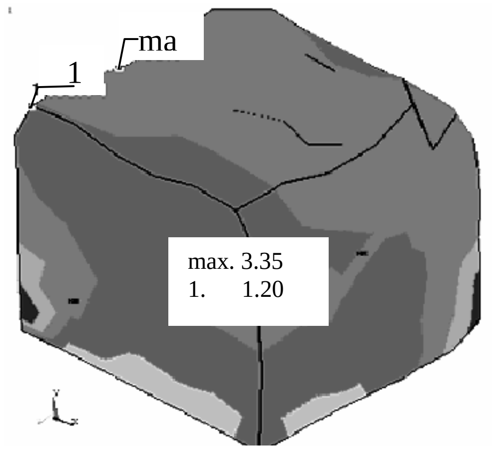

Fig. 9. Stresses in the supporting tooth. Total crown.

1. without the crown (only sticking WE on the border 3);
2. with partial and total crowns.

Conditions of the first variant of the first stage are modelled in the first type. The second type requires the determination of change, put into the stress-strain state of the most dangerous zone by installation a crown on the supporting tooth, welded with the working element. The finite element meshes of the model with partial and total crowns are shown in Fig. 7a, b. Wall thickness of crown is 0.2 mm, material is KHS titanium alloy. Loads on both stages are identical.

The distribution of the principal stresses σ_1 for the first solution type is shown in Fig.8. Difference from corresponding stresses of stage 1 (Fig. 3, a) does not exceed 5% that means good compatibility of these models.

The same results for tooth with total crown are shown in Fig.9. Comparison with Fig.8 shows that crown, having greater Young's modulus than tooth, takes some part of loads from WE on itself and reduces a dangerous stress level in the tooth approximately by 6 times. Comparing of the stage 1 results (reduction of maximum stresses because of DE support) the largest values of tensile stresses in the tooth for "total" prosthetic device is between $1/12[\sigma_B]_{CK}$ and $1/15[\sigma_B]_{CK}$. Thereby, construction of given variant of prosthetic device possesses 12-15-fold reserve of strength under short-time loading.

Installation of total crown is usually accompanied by preparation of supporting tooth or antagonist working surface. That is extremely undesirable for not arranged definitively child

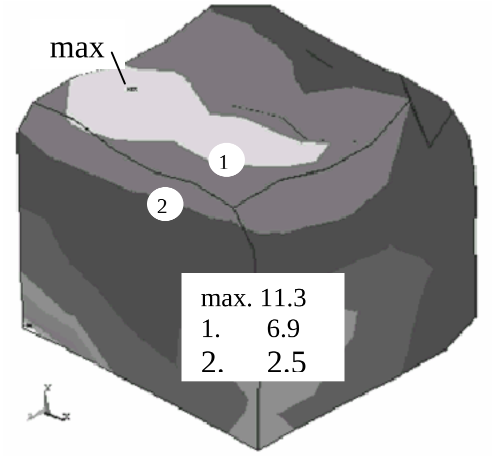

Fig. 10. Principal stress σ_1 in supporting tooth. Partial crown.

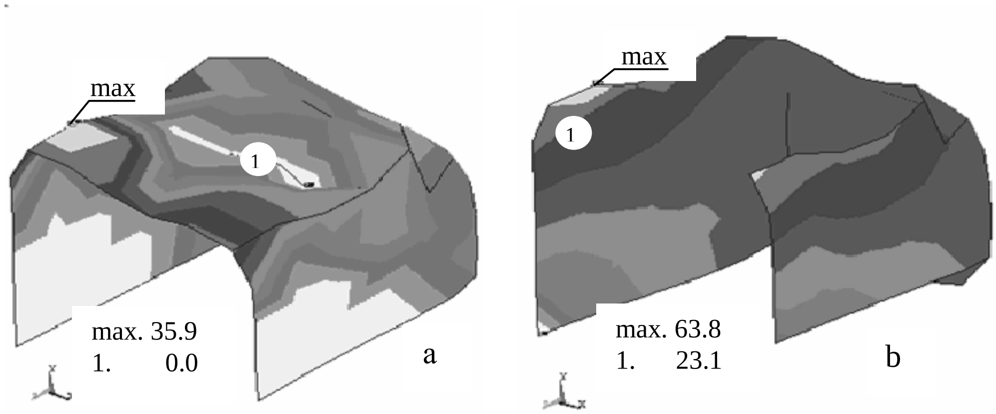

Fig. 11. Distribution of principal membrane stresses: a - in the total crown; b - in partial crown.

teeth. So the possibility to change total crown to partial (lateral), as in Fig. 7,a was researched. In Fig. 10 contours of the principal stresses σ_1 for the last variant of construction are shown. The zone of maximum stresses, in contrast with the total crown, is moved to the border of section, but their value is 2.8 times greater. Comparison with stage 1 results gives 5-6–fold reserve of strength. Thereby, given variant of crown design is acceptable in the case of short-time extreme loads.

Evaluation of strength of the metallic crown itself is also very interesting. Membrane main stress distribution in total and partial crowns accordingly are shown in Fig.11 a, b. Largest stress in the total crown is 36 MPa that corresponds to 15-fold reserve of strength. Stresses in the partial crown are approximately 1.8 times greater, but it does not fail under short loads too.

Problem of prosthetic device durability was not researched in detail. However, it is known, that a threshold strength (stress, under which number of cycles before destroying is infinite) for titanium alloys is 3.5 - 4 times less than short-time strength [4]. An application time of total crown will be practically unlimited in these conditions, but partial crown will save its capacity to work during approximately 10000 cycles under limiting load.

Summary

1. The suggested construction has an adequate safety margin under instantaneous extreme loading for all variants of construction.
2. The variant with the incomplete lateral crown is preferred, since it does not require destroying of child tooth surface. Problem of fatigue in that case can be avoided by making a clearance between WE and antagonist for redistribution of the chewing load to teeth adjacent to the intermediate part of prosthesis.
3. The use of given construction in contrast with traditional designs, makes favourable conditions for child jaws and supporting teeth growth.

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Оценка прочности одной конструкции несъемного мостовидного протеза

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Одним из проявлений детской врожденной патологии является частичная или полная адентия (отсутствие зубов). Для восстановления жевательной способности в этом случае традиционно в детской стоматологии применяются съемные пластинчатые протезы, которые не должны препятствовать росту альвеолярной дуги и не должны искривлять опорные зубы. Однако их эксплуатация причиняет ребенку ряд неудобств: длительный период привыкания, необходимость снятия и чистки после приема пищи и перед сном, нарушение дикции, раздражающее воздействие на слизистую оболочку неба и альвеолярного отростка. Несъемные протезы с двусторонней жесткой фиксацией можно применять только после окончания роста альвеолярных отростков и челюстей.

В данной работе рассматривается новая ,предложенная авторами, конструкция несъемного разборного мостовидного протеза, состоящая из двух тонкостенных полукоронок и закрепленной на них разборной промежуточной части. Целью работы является обоснование работоспособности новой конструкции протеза. Расчет напряженно-деформированного состояния конструкции под нагрузкой проводился с помощью метода конечных элементов, реализованного в программном пакете ANSYS. Оценка прочности проведена в результате двухэтапного расчета. На первом этапе решена задача о контактном взаимодействии элементов промежуточной части протеза с учетом подвижности опорных зубов. На втором этапе проводится оценка прочности в

зоне соединения протеза с зубом и прочности коронки для двух вариантов ее конструктивного исполнения. Анализ напряжений в случае приложения кратковременных экстремальных нагрузок дал возможность выбрать рациональный вариант конструкции. Вопрос о длительной прочности конструкции требует дальнейшего изучения. Библ. 9.

Ключевые слова: детская стоматология, адентия, несъемный мостовидный протез, метод конечных элементов, анализ напряжений

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