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STRESS ANALYSIS OF A UNILATERAL COMPLEX PARTIAL DENTURE USING THE FINITE-ELEMENT METHOD

NAPETOSTNA ANALIZA UNILATERALNO KOMPLEKSNE ZOBNE PROTEZE Z UPORABO METODE KONČNIH ELEMENTOV

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Different types of dental restorations are used in the treatment of a unilateral, free-end saddle. A unilateral, complex, partial denture is one of the indications for this case of partial edentulousness. Consequently, the aim of this study was to stress test the unilateral complex partial denture model and its parts, under load, when changing the length of the free-end saddle. The stress distribution in canines and the first premolar, as the retention teeth, was examined under the influence of physiological and excessive occlusal forces by moving the point of attack in a distal direction. CATIA software was used for the creation of the 3D, fixed restoration unit model, in real size, with the appropriate supporting structures (canine and first premolar with present crowns, alveola, periodontal space) that are connected by the *SD snap-in-latch* attachment to the mobile portion of a partial denture. The mobile portion consists of an acrylate-coated metal base with three teeth (second premolar, first and second molars). The stress analysis, using the finite-element method, was performed under the application of physiological loads of 25 N, 50 N, 75 N and 100 N, and excessive loads of 300 N, 500 N and 700 N in the second premolar region, as well as in the first and second molar region. The results of the analysis showed that the largest amount of load under the application of physiological occlusal forces is positioned on the abutment teeth. Excessive forces are borne by the attachment. The stress analysis, performed on the unilateral complex partial denture model, suggested that the obtained stress values are lower than the limit values at which the plastic deformation in the model occurs.

Key words: unilateral complex partial denture, *SD snap-in-latch* attachment, physiological load, excessive load

Različne vrste popravil zob so v uporabi pri obdelavi enostransko prostega sedla. Enostransko kompleksna delna proteza je ena od indikacij za primer delne edentuloze. Zato je bil namen te študije napetostni preizkus enostransko kompleksnega modela dela proteze in njenih delov pri napetosti pri spremembi dolžine sedla s prostim koncem. Porazdelitev napetosti v podočnjakih in v prvem premolarnem kot retencijskem zobu je bila raziskana pri vplivu fizioloških in prevelikih sil ugriza pri premiku točke napada v distalni smeri. Softver CATIA je bil uporabljen za pripravo 3D fiksnega modela obnove pri pravi velikosti z ustrezno podporno strukturo (podočnjaki in prvi premolarni zob s krono, dlesnijo in peridontalnim prostorom), ki so povezani z vezjo SD snap-in-latch k mobilnemu delu partialne proteze. Ta del je iz kovinske podlage pokrite z akrilatom s tremi zobmi (drugi premolarni, prvi in drugi molarni). Napetostna analiza je bila pripravljena z obojim, fiziološkimi silami 25N, 50N, 75 N in 100 N ter s prevelikimi silami 300 N, 500 N in 700 N v drugem premolarnem ter v prvem in v drugem molarnem delu. Rezultati analize kažejo, da je največja obremenitev zaradi fizioloških ugriznih sil na opornem zobu, prevelike sile pa prenašajo pritrdite. Napetostna analiza je pokazala, da so izračunane napetosti nižje od limitnih vrednosti, pri katerih nastane plastična deformacija modela.

Ključne besede: enostransko kompleksna proteza, pritrditev SD snap-in-latch, fiziološka obremenitev, prevelika obremenitev

1 INTRODUCTION

Different types of dental restorations are used in the treatment of a unilateral, free-end saddle. The final decision on the selection for indication is made on the basis of the patient's consent to treatment, the state of the mouth cavity, the degree of oral hygiene, the periodontal status of the remaining teeth and the degree of residual ridge resorption. Patients with poor oral hygiene represent a contraindication to prosthetic treatment.[1]

Reduced retention, stability and the visibility of the retentive wire extension represent major disadvantages and the cause of dissatisfaction in patients with partial dentures and implant-supported overdentures placed only in the frontal region. The implementation of the osseo-integrated implants in the side region increases stability, partial denture retention and eliminates the need for wire extensions, as Mitrani, Brudvik et al.[2] pointed out in their retrospective study. The implementation of the minimum number of implants, in order to increase the support structure of a partial denture, leads to a change in the Kennedy class I or II of partial edentulousness into a Kennedy class III, denture stabilization and a reduction in the rotational movements. Ohkubo et al.[3] showed that there is no significant difference in movements, during mastication, between a removable partial denture and an implant-supported removable partial denture. The masticatory center, with implant-supported partial dentures, is moved in a more distal direction than with the conventional dentures.

The implementation of implants in the side region is sometimes an impractical solution due to anatomical and/or financial limitations, or a patient's refusal to undergo the necessary extensive surgical procedure. Kuboki, Okamoto et al.[4] compared, in their study, the quality of life in patients with implant-supported dentures, conventional removable partial dentures, and the patients with no dental treatment in a mandibular, unilateral, free-end saddle. The quality of life in the patients with implant-supported dentures was significantly higher than in the others and, as for the patients of the remaining two groups, it was approximately the same. Aesthetics, the absence of pain, chewing and speech are the key factors that influence the quality of life. [5–7]

The progress in technology, along with the one's aspiration to regain the function and appearance of lost natural teeth and to raise the quality of life, leave open the possibility to make dental restorations that do not affect the patient's health and do not require additional surgical procedures. A unilateral complex partial denture is a mobile dental prosthesis, localized to one side of the jaw only. Its role is teeth compensation in a unilateral, shortened, dental series, to restore lost function and to rehabilitate the patient aesthetically. Unlike other types of partial dentures, it does not have a prosthetic plate and arch. This type of dental restoration treatment is considered to have high functional, aesthetic and preventive values.[8-10] The whole complex consists of milled crowns made of a Co-Cr-Mo alloy covered by ceramics and attached by the mobile part. The mobile part is a denture saddle made of the Co-Cr-Mo alloy covered by acrylic. The attachment consists of the primary part (Co-Cr-Mo alloy) and the secondary part (titanium). As far as the dentures and their parts are made of different materials, we tried to show the behavior of this system under physiological and excessive forces by using the FEM.

The aim of this study was to assess the stress distribution in a denture model and its parts, under load, when changing the length of the free-end saddle. The more detailed objectives were:

– stress testing in canines and the first premolar as retention teeth, under the influence of physiological occlusal forces by moving the point of attack in a distal direction;
– stress testing in the canines and the first premolar as retention teeth, under the influence of excessive occlusal forces by moving the point of attack in a distal direction.

2 MATERIALS AND METHODS

To obtain an effective and accurate analysis for the stress conditions and movements by using the finite-element method, it is necessary to design a model that more closely resembles the real object. A fixed restoration piece, with appropriate supporting structures (canine and first premolar with present crowns, alveola, periodontal space) that are connected by the *SD snap-in-latch* attachment to the mobile portion of a partial denture, was created in the CATIA software. The mobile portion consists of an acrylate-coated metal base (Co-Cr-Mo alloy) with three teeth (second premolar, first and second molars). This model was made in actual size (in a 1:1 ratio) to establish the validity of the results obtained.

According to the literature[11], the crown length (height) of the canine model was 9.5 mm, and the mesiodistal width was 7.5 mm. The root length of the model was 16.62 mm. The crown height of the first premolar was 8.5 mm, the mesiodistal width was 7.5 mm, and the root length was 14.5 mm. The average distance of 2 mm between the cement-enamel junction and alveolar bone crest was used in the model, providing the precise root length within the bone. The length of the free-end saddle was 28.27 mm. As for the second premolar, the crown width was 5.16 mm, and the height was 7.5 mm. The crown height of the first molar was 7.5 mm, and the mesiodistal width was 10.5 mm. The crown height of the second molar was 7 mm and the width was 8.22 mm (**Figure 1**).

For the calculation model of the unilateral complex denture a mesh of the appropriate density was generated. All the materials used in the model were isotropic. In an isotropic material, the properties are the same in all directions, and therefore there are only two independent material constants. In most reported studies[12,13] the materials are assumed to be homogeneous, linear and have elastic material behavior characterized by the two material constants of the Young's modulus and the Poisson's Ratio. Therefore, both the teeth and the denture were simplistically modeled as linear, homogeneous and isotropic materials because it was very hard to determine the properties of non-homogenous, anisotropic, composite structures of the analyzed objects. For the structural model the type of finite element used was a 3D ten-node tetrahedral (the option of the 20-node

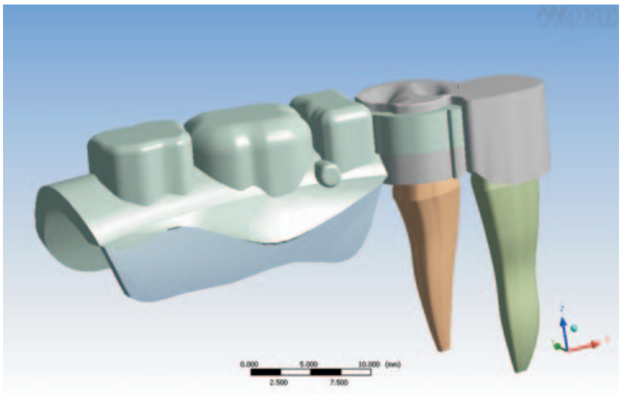


Figure 1: 3D unilateral complex denture model with Snap-in-latch attachment

Slika 1: 3D model enostransko kompleksne proteze s pritrditvijo snap-in-latch brick element).[14] The finite-element mesh of the unilateral complex partial denture model consisted of 357,829 nodes and 186,859 elements.

The visual appearance of the mesh for the unilateral complex partial denture model, with supporting structures, is shown in **Figure 2**.

Applying the finite-element method, the analysis of the stress conditions was performed, under a load of different occlusal forces at the same points along the entire model. The data on the characteristics of the materials used in the stress and movement analysis, using the finite-element method for the tested model, are shown in **Table 1**.

Table 1: Mechanical characteristics of the materials
Tabela 1: Mehanske karakteristike materialov

Material	Young's Modulus of Elasticity, *E*/MPa	Poisson's ratio	Author
Enamel	4.1×10^4	0.30	Rubin
Dentin	1.9×10^4	0.31	Rubin
Root cement	1.37×10^4	0.35	Peters
Pulp	0.000207×10^4	0.45	Rubin
Periodontal ligament	0.00689×10^4	0.45	Reinhard
Gingiva	0.00196×10^4	0.30	Reinhard
Alveolar bone	0.137×10^4	0.30	Gtingor
Gold alloy	7.70×10^4	0.33	Reinhard
Co-Cr-Mo	23×10^4	0.33	Stamenković
Ceramics	6.9×10^4	0.33	Anusavice

Using the finite-element method for the stress and load analyses, the applied force was converted into pressure using the formula $P = F/S$ in order to obtain more realistic images and results.

Using the finite-element method for the stress and load analyses, the applied force was converted into pressure in order to obtain more realistic images and results. The unilateral complex denture model was loaded with different reference forces, while the degree of strain in the retention teeth was being observed. According to various literature data,[15-17] the intensity of the occlusal force is within the range of 50 N in edentulous patients to 1000 N in extreme cases. According to Martinovic[11], their value in an intact tooth is around 780 N, and 210 N in edentulous patients. The values in the range 25–300 N are considered physiological for denture wearers. Forces larger than 300N are considered excessive forces, because they could jeopardize the functional properties of partial dentures. During the testing, all three parts of the free-end saddle (the second premolar region and the first and second molar regions) of a unilateral complex partial denture were loaded, with the aim being to observe the behavior of the whole system and some of its parts in different conditions. A total of 25–700 N of force was applied, with the load in the range from the physiological to the excessive one. The behavior of the denture in relation to the length of the saddle, i.e., in relation to the movement of the point of attack in a distal direction, was also observed. A load analysis of the unilateral complex partial denture was performed using the finite-element method[18-21]. The finite-element method was applied in dentistry, for the first time, in the early 1970s by Farah, Craig and Sikarskie, to optimize the design of dental restorations. The procedure for the analysis of a model using the finite-element method (FEM) included:

- A definition of the virtual model;
- Load inputs and the calculation;
- Analysis of the results.

Four types of finite elements were used for modeling: SOLID 187, CONTA 174, TARGE 170 and SURF 154.

Stress analysis, under load, of the unilateral complex partial denture model using the FEM, can be performed in a four-step process:

- Model geometry for the calculation and finite-element mesh generation;
- Selection of the material and its characteristics;
- Definition of a support;
- Size, direction and load input determination.

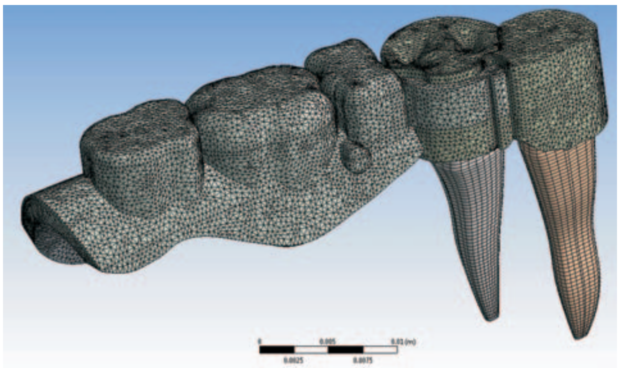


Figure 2: The finite-element mesh of the unilateral complex partial denture model
Slika 2: Mreža končnih elementov za enostransko kompleksno protezo

3 RESULTS

Using the finite-element method, the calculations were performed with the planned load of the unilateral complex denture model (Kennedy class II). The stress values in canines, the first premolar and the attachment of the unilateral complex partial denture model, under different physiological loads, with the point of attack in the second premolar region, are shown in **Table 2**. The stress values in canines, the first premolar and the attachment of the unilateral complex partial denture model, under excessive loads, with the point of attack in the second premolar region, are shown in **Table 3**. With the increased intensity of the applied forces from 25–100 N, the reduction in stress on the retention teeth occurs, while it is increased simultaneously on the attachment. Applying forces larger than 100 N leads to a change in the system behavior and an increase of the stress was

Table 2: The results of the FEM analysis under the application of physiological loads of 25 N, 50 N, 75 N, 100 N to the unilateral complex partial denture model, with the point of attack in the second premolar region
Tabela 2: Rezultati analize pri fizioloških obremenitvah 25,N, 50 N, 75 N in 100 enostransko kompleksne proteze z napadom v drugem premolarnem delu

Force values (N)	Canine (MPa)	First premolar (MPa)	Attachment (MPa)
25	35.58	37.54	221.24
50	33.18	33.60	240.88
75	30.73	29.77	262.18
100	28.31	25.65	285.16

Table 3: The results of the FEM analysis under the application of excessive loads of 300 N, 500 N, 700 N to the unilateral complex denture model, with the point of attack in the second premolar region
Tabela 3: Rezultati analize pri prevelikih obremenitvah 300 N, 500 N in 700 N enostransko kompleksne proteze z napadom v drugem premolarnem delu.

Force values (N)	Canine (MPa)	First premolar (MPa)	Attachment (MPa)
300	12.98	11.39	492.97
500	20.19	38.97	717.18
700	29.86	73.59	946.21

observed in both the retention tooth and the attachment. Under the influence of the forces within the range of 100–300 N, the change of the whole system behavior occurs and the stress is transferred from the retention tooth to the attachment. By applying forces larger than 300 N, the maximum load is concentrated on the attachment, leading to plastic deformation and fatigue destruction. The stress values in canines, the first premolar and the attachment of the unilateral complex partial denture model, under different physiological loads, with the point of attack in the first molar region, are shown in **Table 4**. The stress values in canines, the first premolar and the attachment of the unilateral complex partial denture model, under excessive loads, with the point of attack in the first molar region, are shown in **Table 5**. The stress values obtained in the attachment were slightly lower after the point of attack was moved to the first molar region and with the same amount of load applied. An increase in the force intensity, from 25 N towards 100 N, leads to a reduction in the stress on both the retention teeth and the attachment. Excessive forces (300 N, 500 N and 700 N) lead to an increase in stress on both the retention teeth and the attachment. The stress values in canines, the first premolar and the attachment of the unilateral complex partial denture model, under different physiological loads, with the point of attack in the second molar region, are shown in **Table 6**. The stress values in canines, the first premolar and the attachment of the unilateral complex partial denture model, under excessive loads, with the point of attack in the second molar region, are shown in **Table 7**. Stress reduction in the

Table 4: The results of FEM analysis under the application of physiological loads of 25 N, 50 N, 75 N, 100 N to the unilateral complex denture model, with the point of attack in the first molar region
Tabela 4: Rezultati analize pri fizioloških obremenitvah 25N, 50 N, 75 N in 100 enostransko kompleksne proteze z napadom v prvem premolarnem delu

Force values (N)	Canine (MPa)	First premolar (MPa)	Attachment (MPa)
25	36.18	38.49	203.40
50	34.50	35.38	202.92
75	33.03	32.37	202.47
100	30.12	29.27	202.04

Table 5: The results of FEM analysis under the application of excessive loads of 300 N, 500 N, 700 N to the unilateral complex denture model, with the point of attack in the first molar region
Tabela 5: Rezultati analize pri prevelikih obremenitvah 300 N, 500 N in 700 N enostransko kompleksne proteze z napadom v prvem premolarnem delu

Force values (N)	Canine (MPa)	First premolar (MPa)	Attachment (MPa)
300	17.77	9.46	199.70
500	20.12	27.80	199.26
700	27.68	54.46	200.74

Table 6: The results of FEM analysis under the application of physiological loads of 25 N, 50 N, 75 N, 100 N to the unilateral complex denture model, with the point of attack in the second molar region
Tabela 6: Rezultati analize pri fizioloških obremenitvah 25N, 50 N, 75 N in 100 enostransko kompleksne proteze z napadom v drugem premolarnem delu.

Force values (N)	Canine (MPa)	First premolar (MPa)	Attachment (MPa)
25	37.76	40.05	193.89
50	37.66	38.38	185.43
75	37.43	37.10	178.79
100	37.02	35.78	174.15

Table 7: The results of FEM analysis under the application of excessive loads of 300 N, 500 N, 700 N to the unilateral complex denture model, with the point of attack in the second molar region
Tabela 7: Rezultati analize pri prevelikih obremenitvah 300 N, 500 N in 700 N enostransko kompleksne proteze z napadom v prvem premolarnem delu

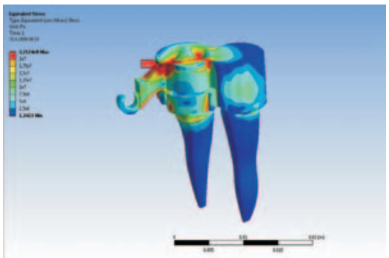
Force values (N)	Canine (MPa)	First premolar (MPa)	Attachment (MPa)
300	36.08	31.42	213.29
500	46.84	31.15	332.98
700	61.05	34.31	475.90

retention teeth, with the increase in load, was also observed in this case.

4 DISCUSSION

The planning phase represents the most important initial phase for making dental restoration, due to the very specific environment in which it should be located. The features of the tissues to be restored and their different behavior in function and at rest, require a through approach to the problem and a full examination of all the aspects of the situation we are to be involved in. When planning prosthetic restorations in the treatment of the unilateral free-end saddle, we are facing the presence of two different biological tissues and the need for the even distribution of the occlusal and other forces on the paradoncium tissue of the remaining teeth and in the mucoperiosteum on the edentulous alveolar ridge. It is almost impossible to achieve an absolute equal load distribution to the supporting tissues; however, the closest load distribution to these two tissues can be achieved by using the elastic bond between the free-end saddle and the retention tooth, together with the extension of the free-end saddle. An important factor in planning is to disable the movements of the free-end saddle that tend to destabilize the denture.

Masticatory forces are found to be variable within the range of minimum and maximum values, they reflect activity and muscle power and are determined by the capacity of the periodontal ligament in patients with natural teeth, or by the sensory capacity of the muco-osseal fundament in patients with removable dental restorations.



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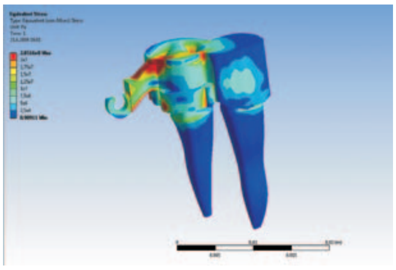

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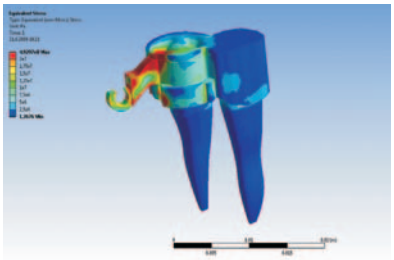

(c)

Figure 3: Changes in the retention teeth and the attachment after force application of 25 N (a), 100 N (b) and 300 N (c) to the second premolar region, using FEM analysis

Slika 3: Spremembe v retencijskem zobu in v pritrditvi pri obremenitvah 25 N (a), 100 N (b) in 300 N (c) v drugem premolarnem prostoru

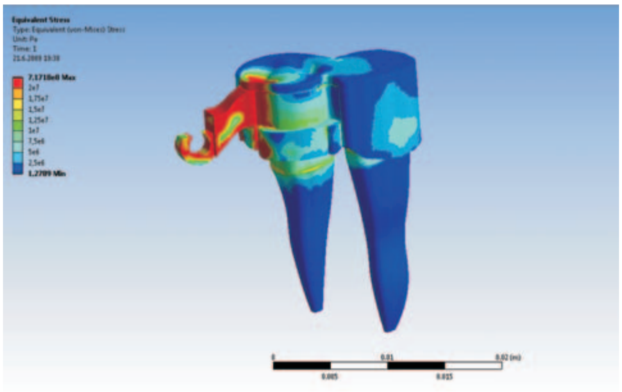

Figure 4: Change in the attachment under the application of excessive load of 500 N with the point of attack in the second premolar region

Slika 4: Spremembe v pritrditvi pri prevelikih obremenitvah 500 N s točko napada v drugem premolarnem prostoru

Literature data by various authors show variable values of the maximum masticatory force. According to Trenouth[22] the maximum bite force in the molar region is within the range 500–700N, and 100–200 N in the incisal region. Tumrasvin et al.[23] came up with the value of 240 N by measuring the maximum bite force of an intact tooth in the upper jaw, and 300 N in the lower jaw. The values for the bite force in the patients with a lack of three teeth were 150 N. Zeljkovic[24] describes the maximum functional force in patients with fixed dental restoration as being similar to patients with preserved dentition, while in the patients with total dentures it is one-third or one-quarter less than in patients with natural dentition. Data obtained by Miyaura et al.[25] pointed out the value was 500 N for an intact tooth and 300 N for a removable denture.

Pellizzer et al.[26] examined, using the finite-element method, the behavior of the implant-supported, partial removable denture regarding a unilateral, free-end saddle

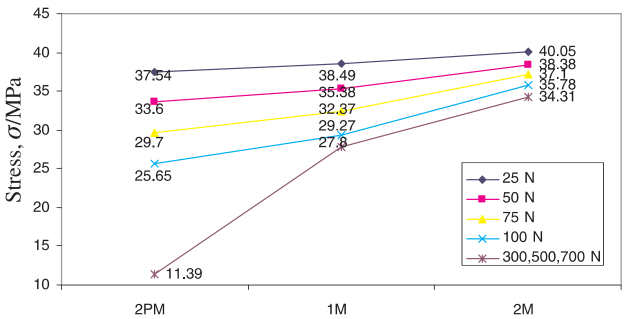

Figure 5: A graph of all the applied forces, their effects, and obtained values of stress in the first premolar of the unilateral complex denture model, when moving the point of attack in a distal direction

Slika 5: Grafikon z vsemi obremenitvami in napetosti v prvem premolarnem zobu modela enostransko komplekne proteze pri pomiku točke napada v distalni smeri under the application of 150 N, 210 N and 300 N forces, in the region of the first and second molars, and came to the conclusion that supporting structures showed a satisfactory behavior when the load was applied. The variety of the maximum bite-force values influenced our selection of the excessive forces (300 N, 500 N, 700 N), so that the unilateral complex denture and its constituent elements could be found under the most adverse conditions.

During the process of modeling and the calculation of the unilateral complex partial denture model, apart from the geometry and the ways to support them, the mechanical characteristics of the materials used for the restorations, as well as the characteristics of the biological supporting structures must also be taken into account. The Young's modulus of the elasticity and the Poisson's ratio were used for the mentioned materials (**Table 1**). Each material has its elastic properties, usually expressed by the modulus of elasticity, in the domain of the elastic behavior of materials.[27]

The results of the FEM analysis showed that the physiological forces (25 N, 50 N, 75 N, 100 N) act primarily on the retention teeth, which accept the major part of the load, while the excessive forces (300 N, 500 N, 700 N) are accepted by the attachment. The application of the physiological forces leads to a stress reduction in the canine and the first premolar, which is confirmed by the presence of the elastic bond between the fixed and mobile portions of the unilateral complex partial denture.

On the basis of the FEM analysis applied, and observing the region of the retention teeth and attachment with the point of attack in the second premolar region under the applied force of 25 N, the intrusion of the first premolar was observed, as the distal edge of the retention tooth. With the increased force intensity up to 100 N, the maximum tooth intrusion and stress reduction in the retention tooth occur. Within the range 100–300 N the increase in stress in the attachment occurs (**Figure 3**, **Table 2**). Applying a force larger than 300 N leads to plastic deformation and fatigue of the attachment, which protects the retention teeth (**Figure 4**).

Various intensities of the physiological (25–100 N) and excessive forces (300–700 N) at all points of attack cause load distribution in the retention teeth that is less than the fatigue limit (the tensile strength is far larger).

The lower stress values obtained in the retention teeth and the attachment when moving the point of attack in a distal direction in the first molar region, are the results of the mesh imperfection and the differences between the first molar and premolar regions ($P = F/S$). By applying the 300 N force in the second premolar region, the 500 N force in the first molar region and the 700 N force in the second molar region, a linear increase in the stress of the retention teeth was observed. Physiological forces of 25 N, 50 N, 75 N and 100 N cause stress on the first premolar showing a growth tendency, when moving the point of attack in a distal direction. This indicates that the excessive force applied at the optimal point of the model causes identical behavior to the physiological load (**Figure 5**).

5 CONCLUSIONS

Applying different load forces within the range of the minimum physiological to the maximum excessive on the unilateral complex partial denture model, and observing the stress values obtained, we came to the conclusion that the stress values obtained in the retention teeth are less than the limit ones at which plastic deformation and fatigue would occur. This proves that this type of restoration, in addition to the reasons of aesthetics and comfort, meets the functional performance criteria.

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