Effect of connector design on the stress distribution of a cantilever fixed partial denture

Original Article

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ABSTRACT

Context: The design of a fixed partial denture (FPD) is very important to reduce the stresses generated over the supporting tissues. The connector area needs specific conditions due to biological and esthetic demands, and must be well assessed especially in the posterior regions. **Aims:** To make a stress analysis of a titanium cantilever fixed partial denture executed with the CAD-CAM system Everest®Kavo, in order to optimize the design of the structure, considering the shape and connector's area. **Materials and Methods:** A finite element analysis mesh was constructed after post-processing the CAD-CAM design. This mesh was submitted to 500 N load to assess the stress distribution within the cantilever (molar) connector. To optimize the design of this connector, a simplified model was created and a stress analysis was done with the software Solidworks®, by modifying the connector's shape and the load. **Results:** The stress values obtained were of 1.8 GPa, 6.5 times higher than titanium yield tensile strength. The stress analysis in the simplified model revealed lower stresses with an elliptical connector (994 MPa), or a 1 mm fillet (812 MPa). Lower loads suggested lower stresses of 540 MPa (125 N load) and 174 MPa (50 N load). **Conclusions:** Cantilever titanium connectors with 5.28 mm^2 area are insufficient to withstand 500 N loads in a molar size cantilever, but may support normal physiologic loads of 50 N. The connectors should be more elliptical than circular to better withstand vertical loads, and the CAD software should permit the design of fillets in the connector/abutment surface. Future studies should evaluate the size of this fillet.

KEY WORDS: Cantilever, finite element analysis, fixed partial denture, stress, titanium

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INTRODUCTION

The design of a fixed partial denture (FPD) is very important to reduce the stresses generated over the tooth/implant and the surrounding bone structure. The connector area, specially the gingival embrasure, needs unique conditions due to biological and esthetic demands, and must be well assessed specially in the posterior regions where the loads are much higher (500-600 N)[1] and the clinical crown shorter.[2-5] The stress values assessed in a cantilever bridge are much worse than in a conventional three element bridge since it is only attached at one end.[6]

These special considerations about the design of a fixed partial denture can be well assessed with a combination of engineering techniques, like the Finite Element Method, and the new computer-aided-design/computer-aided-manufacturing (CAD-CAM) systems.[7,8] The former is a numerical technique for analysis of stress and deformation in structures of any geometry. The number, type and arrangement of the finite elements and its nodes constitute a mesh. The accuracy of the results can be closely related to the reality if an adequate mesh, load and boundary conditions are chosen.[9-12] The latter systems (CAD-CAM) have been developed in order to optimize the confection of fixed partial dentures

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in a functional and esthetic oral rehabilitation.[7] This system had also led to the introduction of new materials, like zirconium ceramics, and to the re-birth of titanium, mainly because these can be machined with this kind of hardware, are biocompatible and can exhibit an excellent functional performance.[7,8,12] Titanium, for example, has mechanical and physical properties that make it a good choice in implants and prosthodontics; Toughness and ductility, resistance to corrosion; Biocompatibility and low density.[13,14] Nevertheless, the ADA Council of Scientific Affairs[13] insists that titanium processing methods and dental technician lab capacity must be well assessed in order to achieve an optimum prosthesis.

The objective of this research was to make a stress analysis of a cantilever fixed partial denture executed in titanium with the CAD-CAM system Everest®Kavo, in order to optimize the design of a fixed cantilever infrastructure, considering the shape and connector's area.

MATERIALS AND METHODS

A fixed partial denture infrastructure with two abutments (e.g. tooth 43 and 45) and two pontics (e.g. tooth 44 and 46) was designed in the CAD-CAM system Everest®Kavo, available in the Faculty of Dental Medicine of the University of Porto, after a scanning of a dental cast with two abutments over two implants. The design of the titanium (grade 2) bridge determined by the software consisted of a 5.28 mm^2 connector area (1.4 mm vertical radius × 1.2 mm horizontal radius) with 2 mm length.

The files generated with this software (*.igs) were converted to Solidworks v.2007 to analyze the CAD design, and then to Abaqus v6.6, a Finite Element Analysis software, available in the Laboratory of Optics and Experimental Mechanics (LOME) of the Faculty of Engineering of University of Porto. The mesh generated had 188707 elements [Figure 1]. The mechanical properties of the titanium grade 2[15] used in the software are shown in Table 1.

The cantilever tooth of the finite element mesh was loaded with 500 N in its occlusal table area with the highest mastication forces just as described by Okeson.[16] In this way the areas with highest stresses will be analyzed. To optimize the design of the connector between the last abutment and the cantilever, a simplified model [Figure 2] was created in SolidWorks v.2007, a 3D mechanical design software (also available in LOME). This type of approach is similar to those of engineers when studying bridge design, optimizing the geometry according to the stress distribution generated by the loads. The dimension of the cantilever tooth (premolar and molar size), the connector's area and geometry (circular, elliptic and gingival embrasure radius) and different mastication forces were tested in this simplified model.

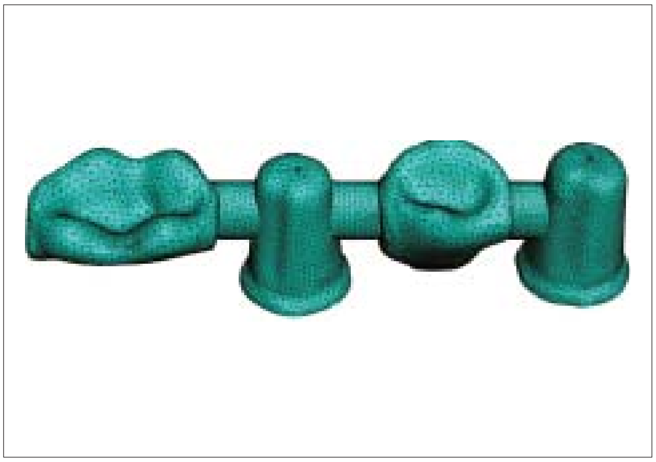

Figure 1: Finite element mesh of the bridge designed with the Everest®Kavo software

Table 1: Mechanical properties of titanium grade 2

Titanium grade 2	
Ultimate tensile strength	344
Tensile strength, yield	275-410
Modulus of elasticity	105 GPa
Poisson's ratio	0.37
Fatigue strength	425 MPa (30000 cycles)

RESULTS

In the first stress analysis within the finite element mesh, the stress values obtained after a load of 500 N on the cantilever tooth were of ≈1,8 GPa [Figure 3]. This value is very high compared to the mechanical properties of titanium [Table 1]. To optimize the design of this area with the highest tensions, a simplified model was built where we could change the area of the connector and the cantilever dimensions. In this model and with a 500 N load applied over the occlusal surface of the cantilever tooth, the von Mises stress values obtained were of 1.044 GPa [Figure 4], 3.8 times higher than the yield tensile strength (YTS) of titanium (276 MPa). The modification of the connector's design to a circle with the same area, but a 1.3 mm radius, raises the stress values to 1.2 GPa [Figure 4]. If the connectors are more elliptical, with a vertical radius of 1.68 mm and a horizontal radius of 1 mm (same area), the von Mises stress values are slightly lower (994 MPa) [Figure 4].

The introduction of a 1 mm fillet, or chamfer (defined in mechanical engineering as a concave easing of an interior corner of a part used to reduce stress concentration) in the junction between the connector and the abutment tooth lowers the von Mises stress

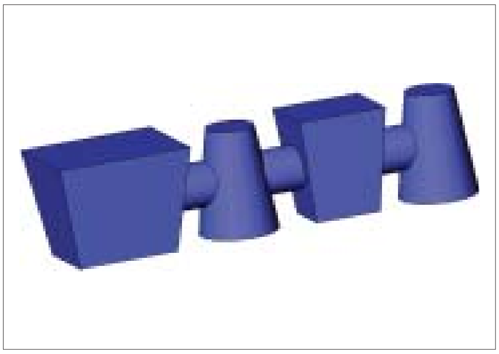

Figure 2: Simplified model of the cantilever bridge

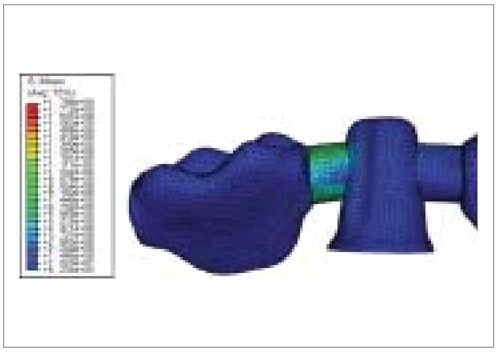

Figure 3: Stress values in the cantilever tooth after 500 N load

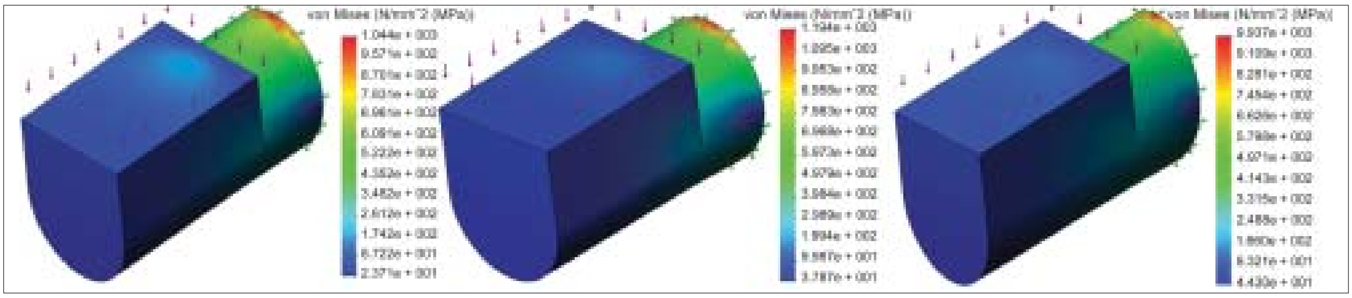

Figure 4: Loading (500 N) of the cantilever tooth with an elliptic connector of 1.4×1.2 mm (left), circle connector of 1.296×1.296 mm (middle) and elliptic connector of 1.68×1 mm (right) [500 N; Connector Area = 5.28 mm^2]

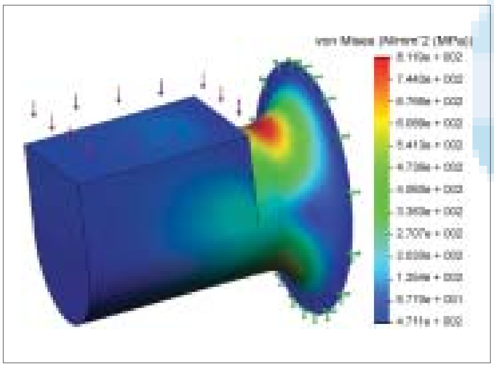

Figure 5: 1 mm fillet in the mesial surface of the connector

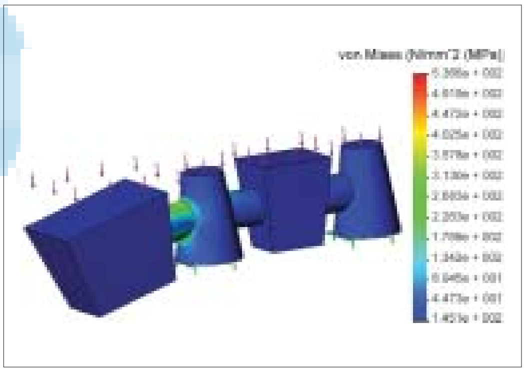

Figure 6: 500 N load distributed over the four teeth (125 N/tooth). Original connector shape

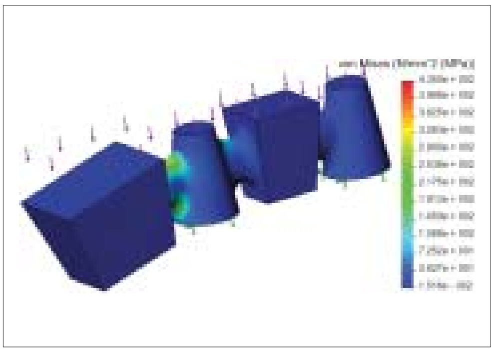

Figure 7: 500 N load distributed over the four teeth (125 N/tooth). Connector shape more elliptical with a 1 mm fillet in the interproximal connector's surface

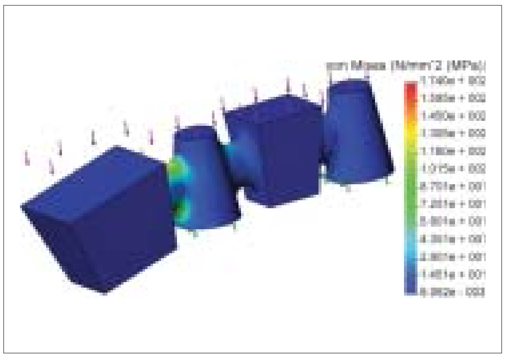

Figure 8: 200 N load distributed over the four teeth (50 N/tooth). Connector shape more elliptical and with a 1 mm fillet in the interproximal connector's surface

values to 812 MPa, still higher than the yield tensile strength of titanium [Figure 5].

The distribution of the 500 N load over the four teeth (125 N per tooth) of the original fixed partial denture design returns values of 540 MPa in the cantilever connector [Figure 6]. The application of the 1 mm fillet and the most eliptical shape, both tested before, lowers the von Mises stress values to 435 MPa [Figure 7], a value only 1.6x higher than the YTS of the titanium. With a 200 N load over the four teeth (50 N/tooth), the von Mises stresses are below (174 MPa) the yield tensile strength of the titanium grade 2 of this system [Figure 8].

DISCUSSION

The shape of the connectors, mainly in the occlusal and gingival embrasures and the area dimension, had been studied by different authors. According to Oh and Anusavice,[4] the fracture resistance of a dental bridge, with three elements, is mostly affected by the radius of the gingival embrasure: As the higher the radius, the higher the probability of fracture. Another study by Eraslan[5] with finite element analysis and a sample of a posterior cantilever bridge (metal-ceramics vs. all- ceramics; molar size pontic vs. pre-molar size pontic) reported that the stresses in the cantilever connector are very high, specially with an all-ceramics bridge, and a molar size pontic.

Our study results show that in a cantilever titanium bridge, the mesial surface of the connector has the highest stress values due to its lever effect. The highest stresses were achieved in the gingival embrasure (1.786 GPa). This results are similar to those obtained by Rommed. [17] This author made a finite element analysis (2D) of a two-unit FPD cantilever, with a 3 mm vertical dimension connector in a gold alloy. A 50 N load was applied in an axial direction. As suggest by Rommed[17] the simple beam theory supports the result of a higher displacement in the cantilever tooth when loading is directly applied to it. The highest tensile stresses were found in the gingival embrasure and the highest compressive stresses were located in the occlusal embrasure.

The simplified model that was built made it possible to optimize the connector design, mainly with the introduction of the 1 mm fillet in the interior corner of the junction between the connector and the abutment. Although the CAD design makes a $\approx 90°$ angle between the connector and the abutment, this could never be achieved with a bur due to its shape and size (radius). The CAD-CAM Everest®Kavo has burs with minimum 1 mm size, which makes the 1 mm fillet of our simplified model possible and correct.

Mastication loads are very difficult to measure. The normal mastication loads are of 10-50 N,[18] but the highest load found in the literature was 4430 N.[19] According to Brekhus[20] the highest load depends on sex, and is between 358 N and 644 N, being higher in males. Howell[21] cites values between 413-898N, higher in the molars. Williams[22] reported highest loads over molars between 300-500 N. The 500 N that have been used in this study are considered as an extreme condition by some authors, since it is difficult to be applied in only one tooth during mastication.[23,24] Usually, the maximal bite force is a common parameter to use in stress analysis studies.[5]

With the 5.28 mm^2 area automatically established by the CAD software, the von Mises stress values obtained with a 500 N load are much higher than the yield tensile strength of titanium, and the connector would definitely fracture. The introduction of a more elliptical shape, and a fillet in the junction of the connector with the abutment lowers the von Mises stresses, and the reduction of the load to levels of 125 N per tooth puts the stress values near 435 N, closer to the yield tensile strength of titanium, but still higher. This load of 125 N is lower than the highest loads registered by the authors mentioned before.[18-20,23,24] However, 125 N is a value closer to the 100 N applied by other authors in their studies.[5,25-27]

Titanium is a linear material. With a simple mathematics rule, if we have stress values of 435 N with loads of 125 N, the maximum load that can be applied not to exceed the YTS of titanium should be approximately 79 N. As such, we have decided to lower the loads to 50 N per tooth, as in the Rommed study[17] If the loads applied over the infrastructure are of 50 N per tooth, which are considered to be normal mastication loads, according to Bosman,[18] the stresses are much lower, and the dental bridge has a successful prognosis.

Within the limitations of this study we can conclude the following:

- A cantilever titanium connector with 5.28 mm^2 area is insufficient to withstand 500 N loads in a molar size cantilever, but may support normal physiologic loads of 50 N.
- Connectors should be more elliptical than circular to better withstand vertical loads.
- CAD software should permit the design of chamfers in the connector/abutment surface. Future studies should evaluate the size of this chamfer.

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