Stress analysis of cantilever-fixed partial denture connector design using the finite element method

Análise de tensões de desenhos de conectores de pontes cantilever pelo método dos elementos finitos

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Abstract

Purpose: To analyze the stress distribution on a cantilever-fixed partial denture after simulation of maximum mastication loads in order to optimize its design.

Methods: A cantilever-fixed partial denture framework was designed in the CAD-CAM system Everest®Kavo v2.0 using two materials, titanium and zirconium, with connectors of 5.28 mm² and 9.05 mm², respectively. A finite element model was built for stress analysis using simulations of mastication load.

Results: For zirconia, only the molar cantilever with the smaller connector area and a 0.5-mm fillet exceeded the considered threshold resistance value of 575 MPa. All the other designs yielded resistances below this value. For titanium, only cantilevers with 9.05 mm² connector area and fillets of 1 or 1.4 mm presented stress values inferior to titanium yield strengh.

Conclusion: Within the limitations of this study, it can be concluded that titanium cantilever-fixed partial denture frameworks with a 5.28 mm² connector area cannot support maximum mastication loads; frameworks of this material require larger connectors with fillets introduced in the gingival embrasure. Zirconia, however, supports maximum bite forces in most situations with both molar and premolar design cantilevers. Precaution should be taken when dealing with smaller connectors of 5.28 mm².

Key words: Fixed partial denture; Yttria-stabilized tetragonal zirconia polycrystals; ceramic; titanium; dental stress analysis

Resumo

Objetivo: Analisar a distribuição de tensões em próteses parciais fixas em *cantilever* após aplicação de cargas simuladoras da mastigação, de forma a otimizar o seu desenho.

Metodologia: Obteve-se a infra-estrutura de uma prótese parcial fixa em *cantilever* no sistema CAD-CAM Everest®Kavo v2.0, considerando dois materiais: titânio e zircônia, com conectores de 5,28 mm² e 9,05 mm², respectivamente. Gerou-se um modelo de elementos finitos, onde foram efetuadas análises de tensões com cargas simuladoras da mastigação.

Resultados: Para zircônia, apenas o *cantilever* molar com área de conector mais reduzida, e concordância de 0,5 mm, excedeu o valor de resistência 575 MPa. Para o titânio, apenas o *cantilever* de 9,05 mm², com concordâncias de 1 e 1,4 mm, apresentou valores inferiores à tensão do titânio.

Conclusão: Dentro das limitações deste estudo pode-se concluir que as infra-estruturas de titânio em *cantilever* não suportam cargas mastigatórias máximas com uma área de conector de 5,28 mm² e requerem conectores de áreas superiores, com concordâncias introduzidas na embrasura gengival. A zircônia geralmente suporta forças mastigatórias máximas com *cantilever* molar ou pré-molar. Deve-se ter precaução quando a área dos conectores é reduzida para 5,28 mm².

Palavras-chave: Prótese parcial fixa; cerâmica de policristais de zircônia tetragonal parcialmente estabilizada pelo ítrio; titânio; análise de tensões

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Introduction

Thorough assessment of the mechanical properties of dental materials is crucial for the development of successful oral rehabilitation. The usefulness of such materials is defined by mechanical laws dealing with the effects of different forces on bodies, which are usually expressed as stresses and strains. In the oral cavity, dental prostheses are subjected to complex forces that produce bending or flexural stresses that have different effects on conventional three-element fixed partial dentures and on cantilever-fixed partial dentures. Conventional three-element dentures are subject to compressive stresses in the occlusal embrasure and to tensile stresses in the gingival embrasure, while the opposite occurs in a cantilever-fixed partial denture (1).

A cantilever-fixed partial denture is defined as a fixed partial denture with abutment(s) in only one end in which the other end is unattached (2). The stress forces generated in cantilever-fixed partial dentures are generally higher than in a conventional three-element fixed partial denture, due to physical principles related to the size of the arm supported only in one end.

The design of the framework, especially of the embrasures and the connectors, of a cantilever-fixed partial denture is critical for its proper function (3-7). The design should respect biological, esthetic and functional principles, considering the region of the oral cavity where it will be situated and taking into account the fact that clinical crowns are usually of reduced dimensions. Dentures must be small enough to allow sufficient space for ceramic veneering and for oral hygiene procedures, but they must also be able to withstand masticatory loads in the range of 500-600 N (8,9).

Specific features of the design of cantilever-fixed partial dentures can be analyzed using a combination of engineering techniques and the CAD-CAM dental systems (10,11). The latter systems allow optimization of the design of prosthetic frameworks for functional and esthetic oral rehabilitation (10) and have led to the introduction of new materials such as zirconia and alumina ceramics, as well as the "re-birth" of titanium, in the construction of dental prostheses. These materials are used because they can be machined with this kind of hardware, are biocompatible and exhibit excellent functional performance (10-14).

Engineering techniques such as photoelasticity, holographic interferometry and the finite element method can be used to analyze stress distribution in implants and prosthodontics. The finite element method is a numerical method for analysis of stress and deformation in structures of any geometry that involves the discretization of a structure into finite elements that are connected by nodes. Although the number, type and arrangement of these elements may affect the accuracy of the results, it has been shown that the method can be used to obtain a useful approximation of the actual stresses and deformations for particular structures (14-17).

The objective of this research is to analyze the stress distribution on a simplified model cantilever-fixed partial denture and to compare the effects of simulated maximum masticatory loads on two materials, titanium and zirconia, in order to optimize its design.

Methods

A fixed partial denture infrastructure with two abutments and two pontics (e.g., abutments in 43 and 45 and pontics in teeth #44 and 46) was designed using the CAD-CAM system Everest®Kavo v2.0 (available in the Faculty of Dental Medicine of the University of Porto) using two materials, titanium and zirconia. The framework design, which was pre-determined by the software, consisted of a 5.28 mm^2 connector area (1.4-mm vertical radius * 1.2-mm horizontal radio) for titanium and a 9.05 mm^2 (1.8-mm vertical radio * 1.6-mm horizontal radio) for zirconia (Fig. 1).

In order to verify the CAD design, the files generated using this software (*.igs) were converted to SolidWorks®2007, a 3D mechanical design software (available in the Laboratory of Optics and Experimental Mechanics of the Faculty of Engineering of University of Porto). To optimize the design of the cantilever connector, a simplified model adapted from the initial CAD design was created, and a stress analysis was done using Ansys® Simulation 11.0 software. The creation of models with a simplified geometry before modeling a 3D real-shape of the final structure is a common approach in engineering (18), as well as in oral biomechanics studies using the finite element method (19). In this manner, it is possible to identify the critical areas of the structure so that its design can be optimized.

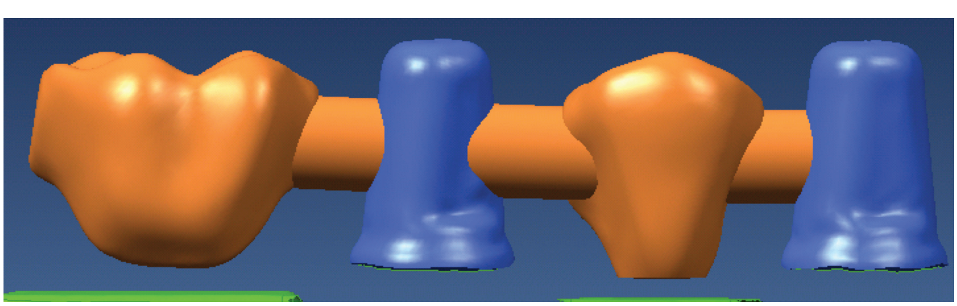

Fig. 1. Fixed partial denture framework design.

The mechanical properties of the materials used in the software were obtained from the vendors' materials datasheets and from Matweb®, an internet scientific database of materials available at www.matweb.com.

The dimensions of the cantilever tooth (premolar and molar size) and the connector's area and design (elliptic and gingival embrasure radius), assuming a 500 N load distributed over the fixed partial denture (125 N per tooth), were tested in this simplified model (Fig. 2).

The simplified model represented in Figure 3, a titanium framework with a molar cantilever, used 9,783 tetrahedral elements with 17,381 nodes. The other models also used tetrahedron elements, but had no more than 19,500 nodes and 11,000 elements due to the increased amount of material in the fillets. In the case of the titanium framework with a pre-molar cantilever and without fillets, there were 7,968 tetrahedron elements and 14,271 nodes. For the simulations with fillets, there were no more than 9,500 elements and 16,800 nodes.

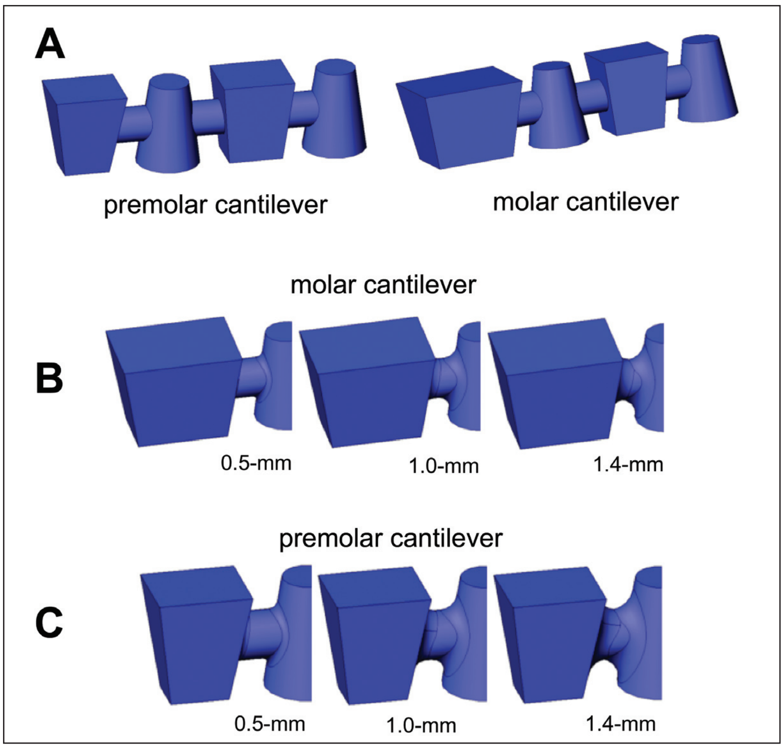

Fig. 2. (A) Simplified model of the titanium framework design with a premolar (left) and molar (right) cantilever.
(B) 0.5-mm, 1.0-mm, and 1.4-mm fillets in the molar cantilever (from left to right).
(C) 0.5-mm, 1.0-mm, and 1.4-mm fillets in the premolar cantilever (from left to right).

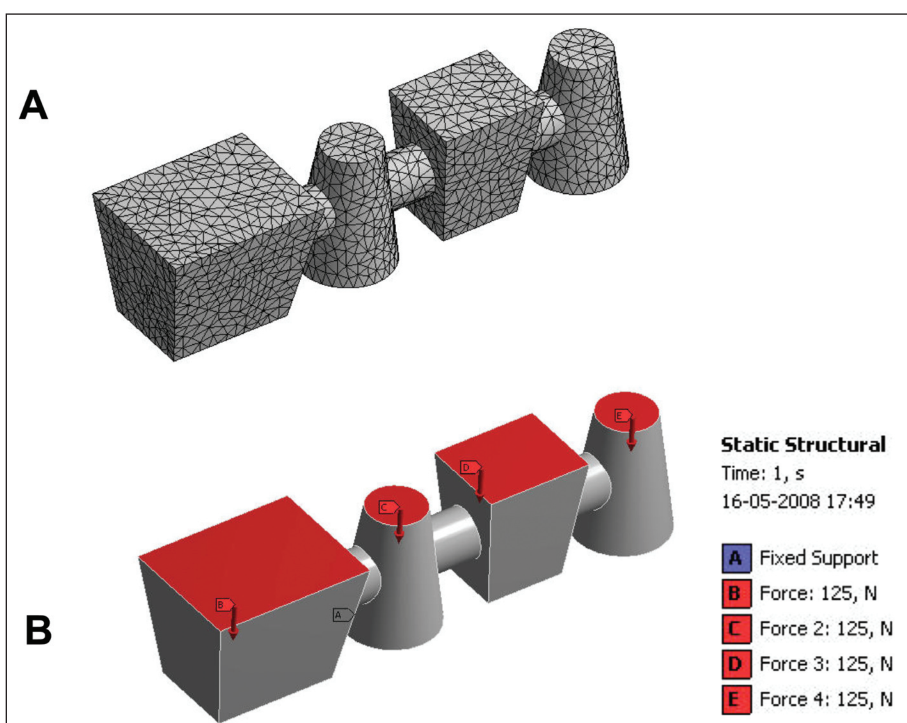

Fig. 3. (A) Finite element mesh of the simplified model of the cantilever-fixed dental prosthesis framework in titanium.
(B) Load distribution over the fixed partial denture (500 N, 125 N per tooth).

For the simplified model of the zirconia framework with a molar cantilever and without fillets, there were 9,701 tetrahedron elements and 17,134 nodes. For this model with fillets, there were no more than 11,350 elements and 19,700 nodes. The zirconia model with a pre-molar cantilever and without fillets had 7,875 tetrahedron elements and 14,119 nodes. The remaining models with fillets had no more than 9,900 elements and 17,000 nodes.

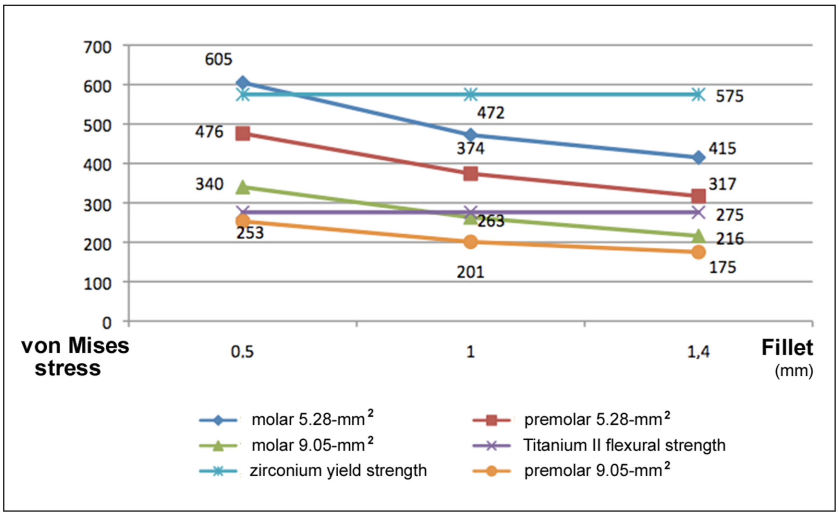

Fig. 4. Graphic representation of the von Mises stresses obtained under a 125 N load for different CAD designs.

Results

The results obtained using a 125 N load over the cantilever tooth occlusal table are summarized in Figure 4. With zirconia, only the molar cantilever with the smaller connector area (5.28 mm^2) and a 0.5-mm fillet exceeded the threshold resistance value of 575 MPa. All the other designs yielded resistances below this value. For titanium, only the cantilevers with 9.05 mm^2 connector area and fillets of 1- and 1.4-mm yielded stress values inferior to titanium yield strength (sample images are presented in Fig. 5).

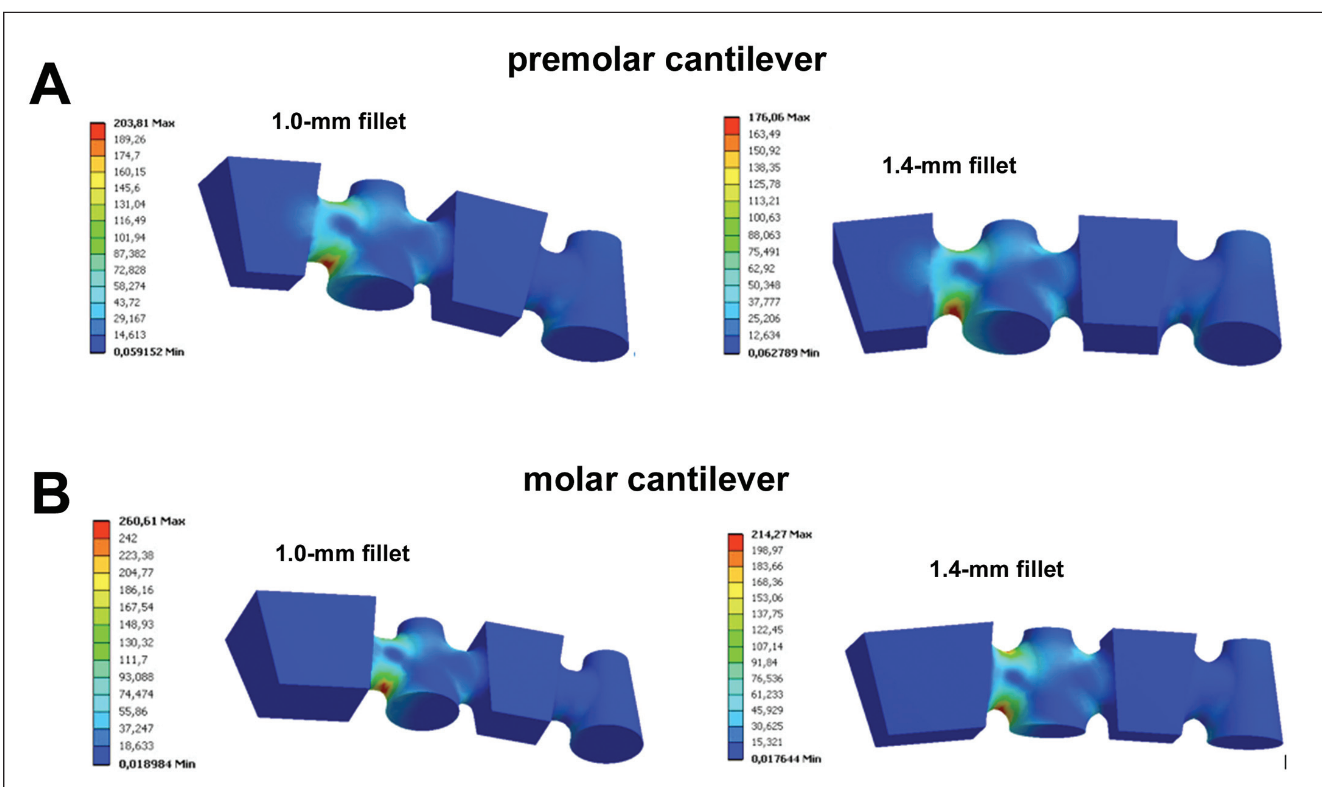

Fig. 5. Fixed dental prosthesis framework design. Connector area of 9.05 mm^2. (A) Premolar cantilever; 1-mm (left) and 1.4-mm (right) fillet. (B) Molar cantilever; 1-mm (left) and 1.4-mm (right).

Discussion

A model of a cantilever-fixed partial denture with a simplified geometry was studied using the finite elements method. Although a "real" framework was designed with the Everest CAD software, a model with a simplified geometry was developed so that design details that increase the complexity of the model could be excluded. Using finite element software, it is possible to use such a simplified model to identify critical areas with higher stresses and study the optimization of its design before modeling a 3D real-shape framework.

The finite element method is a very successful computational method used in engineering since the 1960s. It has proven application in dentistry studies, although assumptions must be made in modeling dental structures, especially with regard to structure geometry and boundary conditions. In spite of this, the finite element method can be effectively used in the analysis of oral rehabilitation structures (15,17).

Using this method, we performed a stress analysis of a cantilever-fixed partial denture using a load of 125 N per tooth. In stress analysis studies, the load values normally used correspond to the maximal bite force, typically 500 N (20). Because it is very unlikely that such a force would be applied to only one tooth during mastication (20), we assumed a load distribution over the fixed partial denture of 125 N per tooth. Under these load conditions, the highest von Mises stresses found in this study were localized in the gingival embrasure for both materials.

The value of reference for von Mises stress analysis of models using a titanium framework was the yield strength. Because the framework requires a veneer ceramic, stresses higher than titanium yield strength are not allowable due to the probability of ceramic fracture. In this study, only connectors with areas greater than 9.05 mm^2 and fillets of 1 and 1.4 mm presented inferior strength values. For zirconia, a value of 50% of the flexural strength was considered (*e.g.*, 1,150 N/2 = 575 N). Failures of a ceramic framework are due to continuous load cycles that exceed the mechanical strength of the material. In previous studies (6,16), a value of 50% of the flexural strength has been considered as the ceramics limit under fatigue cycles. In this study, only the smallest connector area of 5.28 mm^2 with the larger cantilever and no fillet yielded a flexural strength below thisvalue.

Considerations regarding the shape of the denture framework are very important. In 2007, Tsumita (7) concluded that the shape of the framework in an all-ceramic fixed partial denture, especially the pontic-connector interface, strongly affects stress distribution in the framework with probable repercussions in the layering porcelain. Other authors, such as Oh and Anusavice (5) and Dornhofer (3), reported that the radius of curvature at the gingival embrasure strongly affects the fracture resistance of fixed partial dentures, which is in concordance with the results of this study concerning the optimization of the gingival embrasure with a fillet.

The results obtained in this research are also comparable to those obtained by Eraslan (4) and Rommeed (21) in previous cantilever stress analysis studies that used a 2D finite element method. Eraslan (4) studied posterior cantilever-fixed partial dentures composed of metal-ceramics and ceramics with different cantilever size and reported that the stresses of the cantilever connector were very high in the gingival embrasure, especially within an all-ceramics fixed partial denture with a molar size cantilever. Rommed (21) studied a cantilever-fixed partial denture with a connector of 3-mm vertical dimension in a gold alloy under a 50 N load and states that the simple beam theory explains the higher displacement in the cantilever tooth when the load is directly applied to this tooth.

Other authors who have used different analysis techniques make similar statements regarding the importance of the connectors' design in fixed partial dentures. Using holographic interferometry in a study of flexion characteristics in a four-unit fixed partial denture, Goldstein (22) concluded that the highest strains were localized in the connectors. Photoelasticity is another technique that can be used in stress analysis studies. Wang (23) used photoelasticity to analyze stress distribution in cantilever pontics in the posterior regions of the mandible and concluded that the length of the pontic is a crucial factor in this type of rehabilitation.

CAD software companies should permit the design of fillets/chamfer in the connector/abutment surface, as CAD engineering software does, since these elements are crucial in the optimization of gingival embrasure design. Future studies should evaluate stress distribution in a real framework design, with special consideration given to the size of the chamfer in the gingival embrasure region.

Table 1. Different variables studied in the simplified model.

	Titanium Grade II	Zirconia
Connector Radius	1.4 (v)* 1,2 (h); 1,8(v)* 1,6 (h)	1.4 (v)* 1,2 (h); 1,8 (v)*1,6 (h)
Connector Area	5.28 mm^2 vs 9.05 mm^2	5.28 mm^2 vs 9.05 mm^2
Cantilever Dimension	Premolar vs Molar	Premolar vs Molar
Fillet in the gingival embrasure	0.5 mm; 1 mm; 1.4 mm	0.5 mm; 1 mm; 1.4 mm
Yield Strength (1) Flexural Strength (2)	275 MPa (1)	1150 MPa (2)
Load	500 N distributed on 4 teeth (125 N per teeth)	

* v – vertical; h – horizontal.

Conclusions

Within the limitations of this study, it can be concluded that a titanium cantilever-fixed partial denture framework with 5.28 mm^2 connector area cannot support maximum mastication loads. This material requires connectors larger than 5.28 mm^2 with fillets introduced in the gingival embrasure. Zirconia, however, supports maximum bite forces in most situations with molar and premolar design cantilevers. However, when dealing with smaller connectors of 5.28 mm^2, the introduction of fillets in the cantilever connector is essential.

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