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Finite Element Analysis of the Influence of Geometry and Design of Zirconia Crowns on Stress Distribution

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Abstract

Purpose: To evaluate the influence of the geometry and design of prosthetic crown preparations on stress distribution in compression tests, using finite element analysis (FEA).

Materials and Methods: Six combinations of 3D drawings of all-ceramic crowns (yttria-stabilized zirconia framework and porcelain veneer) were evaluated: F, flat preparation and simplified crown; FC, flat preparation and crown with contact point; FCM, flat preparation and modified crown; A, anatomical preparation and simplified anatomical crown framework; AC, anatomical preparation and crown with contact point; and ACM, anatomical preparation and modified crown. Bonded contact types at all interfaces with the mesh were assigned, and the material properties used were according to the literature. A 200 N vertical load was applied at the center of each model. The maximum principal stresses were quantitatively and qualitatively analyzed.

Results: The highest values of tensile stress were observed at the interface between the ceramics in the region under the load application for the simplified models (F and A). Reductions in stress values were observed for the model with the anatomical preparation and modified infrastructure (ACM). The stress distribution in the flat models was similar to that of their respective anatomical models.

Conclusions: The modified design of the zirconia coping reduces the stress concentration at the interface with the veneer ceramic, and the simplified preparation can exert a stress distribution similar to that of the anatomical preparation at and near the load point, when load is applied to the center of the crown.

Fully ceramic restorations have long been used in dentistry for their superior esthetics and biocompatibility.[1] The use of zirconia-based ceramics with high fracture toughness (Y-TZP: zirconia partially stabilized by yttrium oxide) increased the indication spectrum of these restorations, allowing for the use metal-free pieces in high-masticatory-load areas.[2,3]

Despite the promising and initially satisfactory laboratory results of Y-TZP and porcelain (feldspathic ceramic) bilaminate restorations, clinical studies have reported the failure of this system during various periods in function.[4-8] The most frequently encountered failure types are chipping and delamination, or, in other words, cohesive and adhesive failure of the porcelain. This illustrates the hypothesis that the weakest material dictates strength in a bilaminate system.

Investigators have studied several factors in an attempt to better understand these failures.[9-20] In the study of restorative materials by in vitro tests, the results with specimens having simplified formats were reported to be constant.[21-36] When no

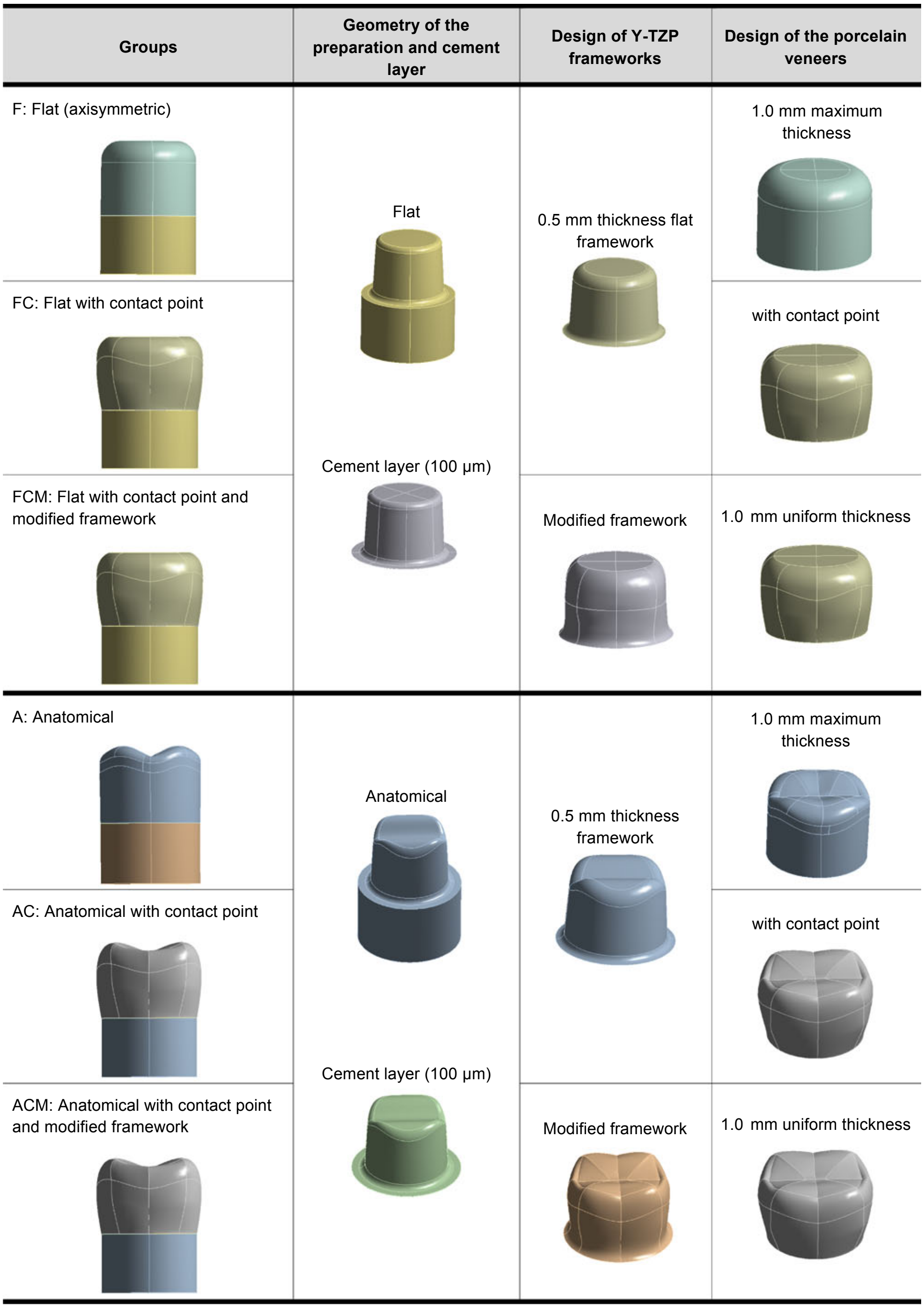

Figure 1 Parameters of the six crowns in relation to the geometry of the preparation, design of the restoration, and thicknesses of the infrastructure and veneering ceramics.

Table 1 Mechanical properties of materials according to published data

Material	Modulus of elasticity	Poisson's ratio	References
G10	14.9	0.31	Yi & Kelly, 2008[44]
Resin cement (Panavia 21 EX)	3.0	0.35	Yi & Kelly, 2008[44]
Y-TZP In-Ceram YZ (Vita Zahnfabrik)	209.3	0.32	Borba et al, 2011[45]
VM9 (Vita Zahnfabrik)	66.5	0.21	Borba et al, 2011[45]

anatomical specimens are used in laboratory tests, it is possible to have more control over the basic mechanical properties of the materials, but the effects of restoration geometry on stress distribution are excluded.[37] Few studies have evaluated the influence of this type of specimen on stress distribution and material strength.[2]

Another important factor in the strength of all-ceramic crowns is the design of prosthetic restorations.[11,14,16,17] The resistance of a bilaminate system is dictated by its weakest component.[38-40] Therefore, increasing the amount of Y-TZP in a crown and improving the porcelain support could improve stress distribution internally.[19]

Thus, the aim of this study was to evaluate the influence of preparation geometry and the design of prosthetic restorations on stress distribution in monotonic compression tests using 3D finite element analysis (FEA). The tested hypotheses were that: (1) the simplified models would adequately reproduce the loading effects of anatomical specimens, and (2) the use of the modified Y-TZP infrastructure would improve stress distribution.

Materials and methods

We used six combinations of all-ceramic crowns with Y-TZP infrastructure veneered with feldspathic ceramic (porcelain), with dimensions corresponding to those of a first molar. We studied the geometry of different G10 preparations (flat or anatomic), with variations in their prosthetic crowns (no proximal contact, with proximal contact, and with proximal contact and modified infrastructure) (Fig 1). For the "contact crowns," the external shapes of the crowns were remodeled, aiming for an approximation to the designs used clinically. Therefore, the contact crowns had their porcelain layer increased, while for the "contact crowns with modified infrastructures," the external shape of the crown was kept, and the framework was made larger to keep the porcelain with 1 mm uniform thickness. G10 is an epoxy resin used in laboratory tests as a material analogous to dentin, to ensure homogeneity of the test substrate, and has been validated by Kelly et al[41] with respect to elastic behavior and adhesion to resin cement.

The 3D geometry evaluations were performed with CAD (computer-aided design) software (Rhinoceros 4.0; McNeel North America, Seattle, WA), according to the BioCad protocol.[42,43] The models were imported into Ansys software (version 13.0; Ansys, Canonsburg, PA) for the preprocessing phase of FEA. In this step, the mechanical properties of the materials were identified, according to published data (Table 1).

The basis for the G10 preparation has displacement restricted at 0 mm in all directions (x, y, z). We considered perfect bonding, with no defects on any model interface, by assigning the bonded contact type to all interfaces (G10/cement; cement/infrastructure, infrastructure/porcelain). The mesh refinement was achieved with 25% relevance for the three existing contacts (contact sizing—relevance 25). All materials were considered isotropic, homogeneous, and linear. The mesh was predominantly composed of tetrahedra with 10 nodes. A 200 N load was vertically applied through a loading force vector, into a knot in the center of each model.

The information from the preprocessing phase was transformed into numeric data with the same processing computational software as used for the static mechanical analysis. We performed a convergence analysis at the 10% level, and the consistency of the results was evaluated by the total displacement of the geometries and uniform voltage gradient according to Von Mises criteria. Analysis of maximum principal stresses (MPS) was used to differentiate areas of tensile (positive) and compressive stress (negative) in the ceramic material (friable), and the results of stress distribution along the structures were compared between and among experimental groups.

Results

The MPS distribution patterns proved to be quite similar between and among the studied models, with a significant concentration of tension in the singularity area (area in and around the load application point) (Fig 2). Figure 3 shows a bar graph with the MPS results (MPa) for the studied models. When infrastructure and porcelain were isolated (Fig 2, "Infrastructure"), there was a zone of tensile stress concentration in the inner area of the infrastructure, at its contact with resin cement, whose maximum values (MPa) were: F, flat preparation and simplified crown, 88.1; FC, flat preparation and crown with contact point, 102.1; FCM, flat preparation and modified crown, 102.1; A, anatomical preparation and simplified anatomical crown framework, 103.4; AC, anatomical preparation and crown with contact point, 97.9; and ACM, anatomical preparation and modified crown, 98.9.

Discussion

Despite the known advantages of the bilaminate systems composed of Y-TZP and porcelain, these systems still experience failures. These failures can be associated with diverse factors: low fracture toughness[18] and thickness of the porcelain,[12] inconsistency or differences in thermal expansion between

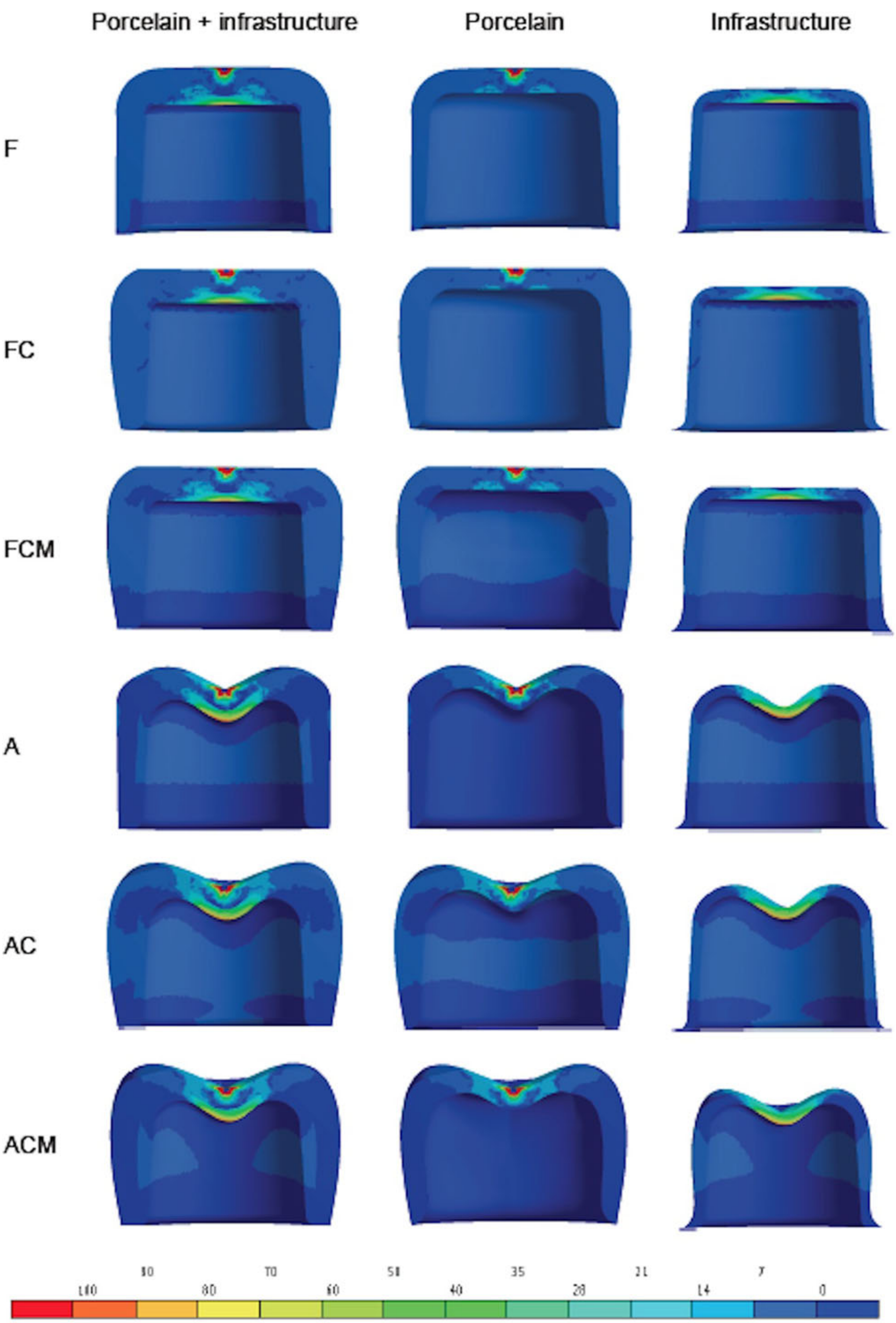

Figure 2 MPS results for the studied models with 200 N vertical load. Standardized scale.

materials,[9] inadequate cooling rate,[15] processing techniques,[10] phase transformation,[13] low thermal diffusivity of Y-TZP,[12] and insufficient support of the porcelain by the infrastructure.[19,20] The present study focused on the thickness, shape, and support of the ceramics.

The stress distribution in the models studied showed similar patterns. The singularity area showed higher tensile value concentrations, suggesting that the fracture would begin there. Slightly soft distribution curves were observed only in this region. When infrastructure and porcelain were isolated, we also observed stress concentration in the inner region of the infrastructure, which is associated with a low modulus of elasticity of the substrate[46] (cement layer and G10 preparation) and bending of the infrastructure; however, these values were significantly

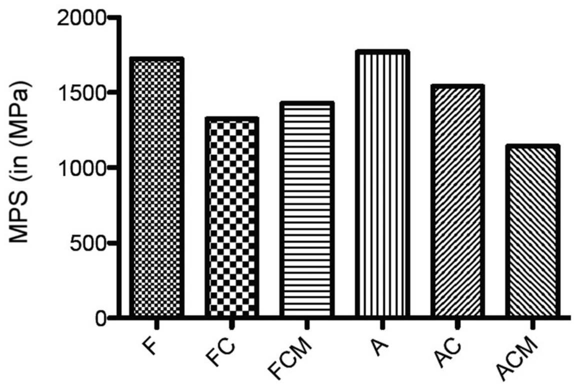

Figure 3 Bar graph with the MPS results (MPa) for the studied models with 200 N vertical load.

lower (ranging from 88.1 to 103.4 MPa) than those of porcelain (ranging from 1143.2 to 1771.5 MPa). With this, and due to the fact that Y-TZP is the more resistant material in this set, we did not focus further on this area in our assessment. The remainder of the model had minimal and regular tensile stresses.

Numerically, the results of this work showed higher MPS values in the simplified models, both flat and anatomical. This can be explained by the lower porcelain content in these models. The porcelain, due to its inferior mechanical properties, is responsible for most of the stress dissipation. Among the simplified models, an increase in porcelain thickness decreased stress concentration in the material, which can occur due to the larger volume available for stresses to dissipate. Despite this, which was also observed in another study,[31] there is no consensus in the literature, since some studies have reported an opposite effect,[14,16] and others found no significant effect of porcelain thickness on the fracture strength of restorations.[29]

Between models C (contact) and CM (modified contact), values were similar, and this may be associated with the fact that the drawings in question had little difference in their Y-TZP volumes in the region of load application. The simulation of crowns with larger dimensions, which significantly alter the ratio between zirconia and porcelain, could result in differences in stress values, as observed by Kokubo et al.[19] Thus, the second hypothesis was partially accepted.

In this study, we also compared the simplified model (F) with drawings having clinical potential (AC and ACM). Among these models, the stress distribution was similar inside the geometry of each model, but the difference between the MPS suggests that when ACM or AC models were replaced by F, there may be an overestimation of material strength data; however, taking into consideration the difficulty of standardizing the manufacture of AC or ACM specimen types for laboratory tests, the choice of simplified models can be justified as a means of reducing bias in the work. In this case, it would be necessary to take such differences into account in the results.

This study did not consider the residual stress that may result from the crown manufacturing process and assumed that all materials had perfect unions and total absence of internal defects. Therefore, the "values" observed here should not be directly compared with other noncomputational laboratory findings, but rather should be compared with each other. The load application was standardized to allow for comparison between and among models and also may differ from what is found in laboratory tests. Furthermore, precisely loading differs from the facet contacts that can be clinically found[47] and that better distribute the load.

Clinical studies with crowns or posterior fixed partial dentures (FPD) of bilaminate ceramic (Y-TZP and porcelain) reported survival rates between 73.9 and 100% after 2 to 5 years of observation.[4-8] The chipping and surface wear of porcelain were mainly responsible for system failures. Chipping is not usually responsible for the need to replace these restorations. Although representing a failure of the material, it does make the restoration susceptible to repair; however, in some studies, extended fractures and delamination have been observed in porcelain and have led to the replacement of restorations.[6-8] Infrastructure failure, although rare, was reported in two cases from a total of 158 FPDs, in Christensen and Ploeger's[8] study.

One factor that can distance the findings of clinical and laboratory studies is that clinics are not subject to standardized conditions, with variations in thermal contraction, geometry, surface treatment, environmental conditions, and load orientation. Nevertheless, the results of the present study suggest cohesive failure of porcelain as the main reason for failure of these crowns.

Conclusions

Within the limitations of the present work, we reached the following conclusions:

(1) The modified design of the anatomical zirconia copings reduces the stress concentration at the interface with the veneer ceramic.
(2) The simplified preparation can exert stress distribution similar to that of the anatomical preparations with contact, when load is applied to the center of the crown.

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