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On the failure of ceramic restorative crowns under mastication loads

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Abstract

Ceramics used as restorations in dental crowns are extensively used due to their aesthetic result and corrosion resistance. However, they may fail under usual loads due to intrinsic britleness of ceramic materials. This is especially likely in the posterior region where occlusal forces can lead to deterioration of the dental crowns. This study aims at investigating the behavior of different ceramic used for dental crowns. This analysis is performed by means of numerical modeling using the extended finite element method that allows to follow the evolution of the crack appearance and propagation. For this purpose, a three-dimensional finite element model of the mandible and all its components was developed. Then, we compared the behavior of different materials usually used for dental restorations such as Feldspar ceramic (FC), Hybrid high-performance polymer composite resin (HPP), Lithium disilicate (LDS), Polymer-infiltrated ceramics (PIC), and Yttria stabilized tetragonal zirconia (Zr). All of them were also compared with enamel. Also, we considered two ways for loading the occlusal antagonist surfaces: (i) by applying the displacement on the surface of the first molar; (ii) by applying tooth-to-tooth contact. Zr did not damage in any of both models, while other materials fractured. It can be concluded that Zr, according to the assumptions of this study, is more resistant to occlusal forces than other ceramic materials used in dental restorations.

Keywords: dental ceramics, crown fracture, mastication loading, XFEM

1 Introduction

Several ceramic materials are used for dental restoration providing an aesthetic aspect close to natural teeth. In addition, dental ceramics are resistant to long term degradation inside the oral cavity and are biologically compatible [1]. Also, properties like low thermal and electrical conductivity, high melting point, and resistance to chemical reactions have made dental ceramics widely used in dentistry [2]. The main disadvantage of these materials is their tendency to break, during chewing, and after impact due to their intrinsic brittleness [3, 4]. The analysis of the effects of this structural limitation of this type of materials has been the focus of many previous works [1]. Therefore, understanding the mechanical behavior of dental ceramics is essential for a correct and long-lasting application of these materials [4].

Dental restorations use various types of ceramics such as polycrystalline zirconia tetragonal , (TZP), alumina, mica, feldspar, leucite, lithium disilicate, lithium zirconia silicate, or fluoroacetate [5]. TZP has received most attention from researchers due to its excellent mechanical properties, such as fatigue resistance [6, 7]. Dental ceramics are usually reinforced and stabilized with different oxides such as Yttria (Y_2O_3), alumina (Al_2O_3), magnesium (MgO), and calcium (CaO) among other. A much used combination is Y-TZP [8].

Analysis of the behavior of dental ceramics requires the use of geometric modeling and realistic boundary conditions. To our knowledge, the simulations performed on the mechanical behavior of ceramic restorations did not consider the whole geometry of the mandible and its components. Usually, the geometries include only the tooth studied with the surrounding structure. Also, concentrated loads characterize the occlusal condition. But, the loads that act during the chewing are due to the muscles involved. These simplifications can lead to unrealistic stress distribution in dental structures [9]. This study aims at simulating and comparing the behavior of different dental ceramic materials during chewing by considering actual boundary conditions. For this purpose, first, we solved the bone remodeling process to get mandible bone density distribution. Afterward, the ceramic restorative components were installed at the mandible. The extended finite element method (XFEM) simulated the fracture prediction of the ceramics. Also, the contact between the occluding antagonistic teeth during mastication was considered.

2 Materials and methods

2.1 Geometry

A threshold for CT images in MIMICS 10 was set for performing the manual segmentation of bone and teeth. The result of this segmentation is a three-dimensional geometry of the mandible and teeth. Then, the final geometric model in CATIA using the exported STL was created. As the CT images cannot detect the periodontal ligament, an offset of approximately 0.2 mm per tooth was applied with boolean operations to create it.

After building the mandibular geometry, the ceramic crown and cement layer was modeled. The geometry of the first molar was the base for all models. Afterward, the region was replaced with new dental components, including restorative crown, cement, pulp, and dentin accompanied with surrounding tissues. Simulation with the initial geometry characterizes the initial elastic modulus distribution.

2.2 Loads and boundary condition

Two models for simulating the crack initiation at ceramics were used. In the first one (Fig. 1a), the loading condition on the molar's surface was applied. The second model (Fig. 1b) considers the superior right molars to simulate contact conditions. Thus, the contact between the occluding antagonistic teeth was simulated.

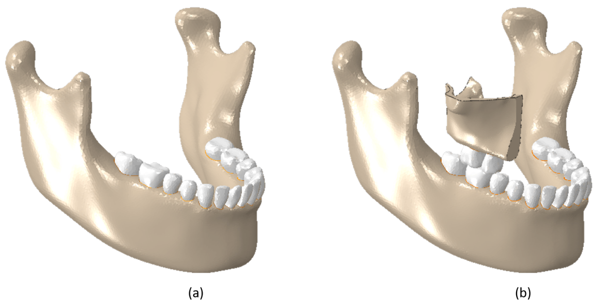

Figure 1: (a) Mandibular geometry (model A), (b) The same geometry of model A beside a section of maxilla containing premolar and first molar teeth and pdls to simulate the contact between the occluding antagonistic teeth during mastication (model B).

The boundary conditions described above were used to get the elastic modulus distribution for the heterogeneous bone considered. To get such distribution, a previous virtual remodeling approach was used which allowed us to characterize the bone tissue properties as in [10, 11]. Afterward, the fracture behavior in the ceramic crown was simulated using the XFEM.

2.3 Material definition

As commented, a bone remolding algorithm was used to determine the bone elastic modulus distribution. During bone remodeling, completely bounded situation was considered. The analyses considered different material parameters for describing the behavior of dental crowns. The material parameters of Lithium disilicate (LDS), Yttria stabilized tetragonal zirconia (Zr), Hybrid polymer-infiltrated ceramic network material (PIC), Feldspar ceramic (FC), and Hybrid high-performance polymer composite resin (HPP) were used for the dental restorative crown.

After crack initiation, crack growth is modeled by strain energy release [12]. The brittle fracture occurs if the strain energy release rate (G) reaches a critical value (G_c). This critical energy release rate is related with the fracture toughness K_{IC} and the elastic modulus (E) as [13]:

$$G = \frac{K_{IC}^2}{E} \tag{1}$$

We implemented the phenomenological bone remodeling model proposed by Jacobs [14]. An exact analysis for bone remodeling requires repetitive processes. In this regard, we implemented the UMAT (User Material) subroutine to update the bone materials used in ABAQUS. A detailed explanation of phenomenological bone remodeling can be found in [10].

2.4 Contact definition

Two models for simulating the crack initiation and propagation were developed. In the first model (Fig. 1a), the displacement is directly applied to the dental surfaces. For the second one (Figure 1b), a surface-to-surface contact condition with friction and finite sliding was implemented between occluding antagonistic teeth. The tooth-to-tooth contact had a frictional coefficient of 0.5.

2.5 Extended finite element method (XFEM)

The XFEM was used to simulate the initiation and propagation of cracks in dental ceramics using Abaqus (ABAQUS 6.11, Dassault Systèmes, Vèlizy-Villacoublay, France). The fracture behavior was analyzed only for dental crowns. The maximum principal stress (MPS) was used as the cracking criterion [13]. This criterion considers the stress ratio (f^e) for determining the initiation of the cracks in the element (e). Cracking begins when MPS exceeds the material's tensile strength. f^e defines as:

$$f^e = \frac{(\sigma_1^e)}{\sigma_{max}^e} \tag{2}$$

where σ_{max}^e is the maximum stress of the ceramic materials (i.e. tensile strength of material, σ_{TS}), and σ_1^e represents the first principal stress. The main advantage of this approach is that the crack plane can be perpendicular to the direction of the MPS. XFEM allows simulating the crack initiation and further propagation without pre-defined path or region and mesh dependence [15].

3 Results

Figure 2 presents the distribution of bone elastic modulus obtained from the bone remodeling simulation of the daily chewing process in the mandible. This simulation considers the order of each tooth's function in the chewing process. As can be observed in Figure 2, the outer surface of the mandible is entirely dense, and the closer we move to the center, the more spongy bone appears. This kind of structure is common in long bones as, for example, the femur. This distribution gives the mandible the necessary resistance to the bending and torsion during the chewing. At the regions close to the teeth, the trabecular bone presents a low porosity allowing the necessary anchorage for the tooth's roots. The simulations of the fracture response of ceramics (Figure 3) used this distribution of the bone elastic modulus as initial condition.

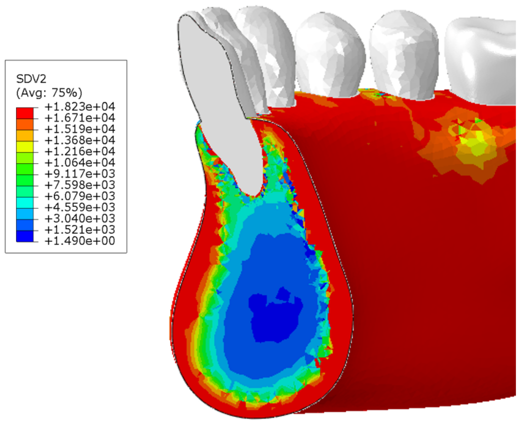

Figure 2: labial-lingual cut section view of elastic modulus distribution in mandible after 720 days of simulation.

Figure 3 presents the local site where the crack begins for model A (Fig. 1a). Although there were four areas for fixing the enamel, only one of these areas was damaged. For the failure models, the value one indicates complete fracture. The value zero indicates a non-fracture state. The Zr ceramic does not fail, while the failure happened for all other ceramic materials.

Figure 4 presents the results obtained using model B (Fig. 1b). In model B, which considers the contact between the upper and lower teeth, the contact area between the two teeth is damaged due to the maximum tensile stresses induced in this region.

4 Discussion

Ceramic materials are widely used in dental restorations. They stand out due to their mechanical properties, biocompatibility, and beauty. The main disadvantage is their tendency to fail during placement or chewing. The dilemma is to increase the strength or toughness of the dental ceramics, but without sacrificing beauty. Studies using numerical methods can help the design of ceramic components. Also, they can test the suitability of different materials for this application. With this aim, we built two 3D geometry models of the mandible (Fig. 1). Then, we simulated several ceramics materials used in dental restorations.

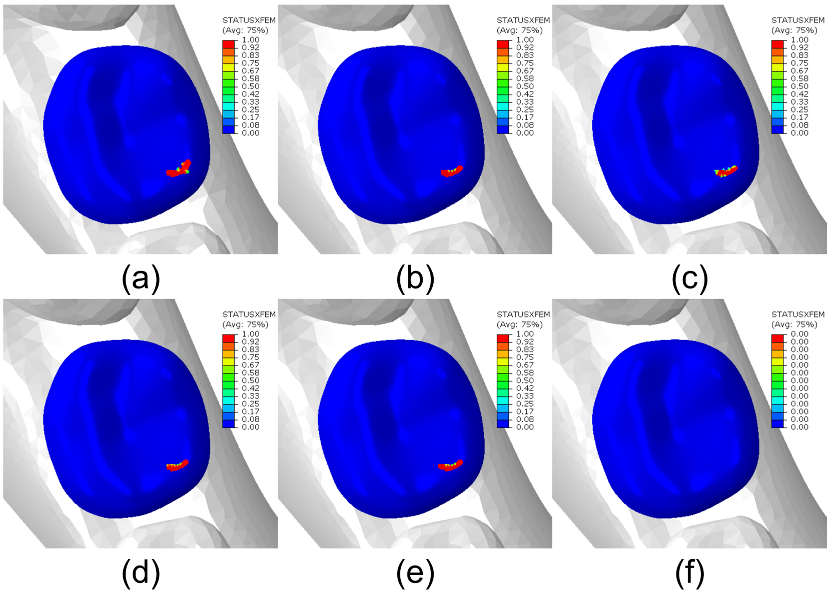

Figure 3: Status XFEM in model A: (a) enamel, (b) FC, (c) HPP, (d) LDS, (e) PIC, and (f) Zr. (0.0 value indicates a crack-free state while 1.0 value indicates a complete crack).

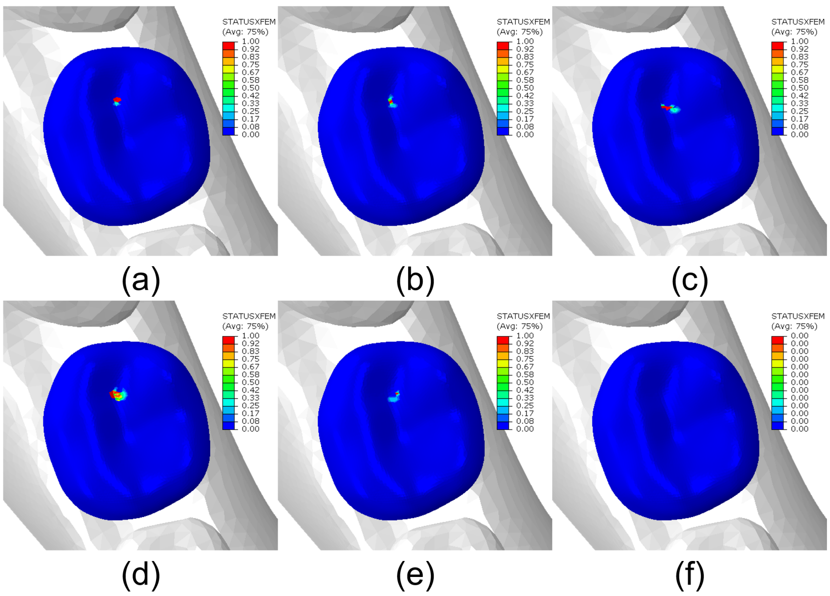

Figure 4: Status XFEM in model B: (a) enamel, (b) FC, (c) HPP, (d) LDS, (e) PIC, and (f) Zr. (0.0 value indicates a crack-free state while 1.0 value indicates a complete crack).

The loading condition is a significant factor in the simulations since experimental and numerical studies show failure in the contact area [16] (see Figure 3). This model considers the application of the displacements on the occlusal surface. For model A, the results present large regions (in gray) of MPS, while the displacement compresses the distal part of the teeth. This behavior leads to the failure of 5 of the 6 materials simulated (Fig. 3). The cracks initiated in the tension region, far from the surface's compressive behavior.

There are several ceramic materials for commercial use in monolithic shapes for crowns in dentistry, which include Lithium disilicate, Yttria stabilized tetragonal zirconia, Hybrid polymer-infiltrated ceramic network material, Hybrid high-performance polymer composite resin, and Feldspar ceramic [13]. The mechanical performance of these materials depends not only on their composition, microstructure, and construction but also on design parameters, preparation, and cusp inclination [13]. Comparing these materials under chewing load in this study showed that LDS, PIC, HPP, and FC act almost similarly, and Zr is more resistant to failure. This result also confirms the ones obtained by Shahmoradi *et al.* [13].

Clinical trials are the first choice for evaluating the long-term clinical behavior of dental materials and techniques. However, high costs lead to narrow results, and meaningful conclusions in these studies require the selection of a sufficient number of restorations as well as the follow-up of 3-4 years [17]. Clinical studies have shown that all-ceramic restorations have a clinically acceptable lifespan with their long-term aesthetic benefits [18]. Various experimental methods have been used to study the mechanical properties of dental materials. Given that the values obtained in these experiments are significantly different from clinical observations [17], as we have shown in this study, the use of the finite element method can, to some extent, study the actual dental conditions.

5 Conclusion

We performed simulations for evaluating the behavior of different dental ceramics. These ceramics were under the action of chewing loads. The results showed that the Zr is the best option for use in the situation studied. This material did not fail in both geometric models used. This behavior follows the results presented in other studies. We can conclude that the choice of the type of dental ceramics can be effective in the success of dental restorations. We saw how necessary the geometric models are to use actual boundary conditions. Bone tissue properties, chewing muscle forces, and tooth-to-tooth contact describe those conditions. The contact condition allowed a better characterization of how the crack begins.

References

[1] Daniel Juica, Natalia Marcus, Fernando Grandon, Vilma Sanhueza, and Michael Wendler. Premature failure of a screw-retained ceramic single crown: A clinical report and fractographic analysis. *The Journal of Prosthetic Dentistry*, 2020.

[2] Elnaz Shafigh and Mehran Ashrafi. A review of mechanical behavior of dental ceramic restorations. *Journal of Mechanics in Medicine and Biology*, 21(08):2150063, 2021.

[3] Sadia Nasrin, Noriko Katsube, Seghi Robert, and Stanislav Rokhlin. 3d statistical filure anlysis of monolithic dental ceramic crowns. *Journal of Biomechanics*, 49:2038–2046, 2016.

[4] Shirin Shahrbaf, Richard van Noort, Behnam Mirzakouchaki, Elaheh Ghassemieh, and Nicolas Martin. Fracture strength of machined ceramic crowns as a function of tooth preparation design and the elastic modulus of the cement. *Dental Materials*, 30(2):234–241, 2014.

[5] Wolfram Höland, Volker Rheinberger, Elke Apel, Christian vanâ€™t Hoen, Marlies Höland, Alex Dommann, Marcel Obrecht, Corinna Mauth, and Ursula Graf-Hausner. Clinical applications of glass-ceramics in dentistry. *Journal of Materials Science: Materials in Medicine*, 17(11):1037–1042, 2006.

[6] Angel L. Ortiz, Camila S. Rodrigues, Fernando Guiberteau, and Yu Zhang. Microstructural development during crystallization firing of a dental-grade nanostructured lithia-zirconia glass-ceramic. *Journal of the European Ceramic Society*, 41(11):5728–5739, 2021.

[7] Dong Xiang, Yongxiang Xu, Wei Bai, and Hong Lin. Dental zirconia fabricated by stereolithography: Accuracy, translucency and mechanical properties in different build orientations. *Ceramics International*, 47(20):28837–28847, 2021.

[8] Alvaro Della Bona, Oscar E Pecho, and Rodrigo Alessandretti. Zirconia as a dental biomaterial. *Materials*, 8(8):4978–4991, 2015.

[9] Natsuko Murakami and Noriyuki Wakabayashi. Finite element contac analysis as a critical technique in dental biomechanics: A review. *The Journal of Prosthodontic Dentistry*, 58:92–101, 2014.

[10] Mehran Ashrafi, Farzan Ghalichi, Behnam Mirzakouchaki, and Manuel Doblare. On the effect of antiresorptive drugs on the bone remodeling of the mandible after dental implantation: a mathematical model. *Scientific Reports*, 11(1):1–20, 2021.

[11] Mehran Ashrafi, Farzaneh Gholamian, and Manuel Doblare. A comparison between the effect of systemic and coated drug delivery in osteoporotic bone after dental implantation. *Medical Engineering & Physics*, 107:103859, 2022.

[12] Boyang Wan, Mahdi Shahmoradi, Zhongpu Zhang, Yo Shibata, Babak Sarrafpour, Michael Swain, and Qing Li. Modelling of stress distribution and fracture in dental occlusal fissures. *Scientific reports*, 9(1):1–10, 2019.

[13] Mahdi Shahmoradi, Boyang Wan, Zhongpu Zhang, Tom Wilson, Michael Swain, and Qing Li. Monolithic crowns fracture analysis: the effect of material properties, cusp angle and crown thickness. *Dental Materials*, 36(8):1038–1051, 2020.

[14] Christopher Rae Jacobs. *Numerical simulation of bone adaptation to mechanical loading*. PhD thesis, The school of the thesis, Stanford University, 1994.

[15] Mahdi Shahmoradi, Boyang Wan, Zhongpu Zhang, Michael Swain, and Qing Li. Mechanical failure of posterior teeth due to caries and occlusal wear-a modelling study. *Journal of the Mechanical Behavior of Biomedical Materials*,

125:104942, 2022.

[16] Ehsan Homaei, Xiao-Zhuang Jin, Edmond Ho Nang Pow, Jukka Pekka Matinlinna, James Kit-Hon Tsoi, and Khalil Farhangdoost. Numerical fatigue analysis of premolars restored by cad/cam ceramic crowns. *Dental Materials*, 34(7):e149–e157, 2018.

[17] Petra C Guess, Stefan Schultheis, Estevam A Bonfante, Paulo G Coelho, Jonathan L Ferencz, and Nelson RFA Silva. All-ceramic systems: laboratory and clinical performance. *Dental clinics*, 55(2):333–352, 2011.

[18] Alvaro Della Bona and J Robert Kelly. The clinical success of all-ceramic restorations. *The Journal of the American Dental Association*, 139:S8–S13, 2008.