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The bending stress distribution in bilayered and graded zirconia-based dental ceramics

Douglas Fabris^a, Júlio C.M. Souza^{b,c}, Filipe S. Silva^b, Márcio Fredel^a, Joana Mesquita-Guimarães^a, Yu Zhang^d, and Bruno Henriques^{a,c,*}

^aCeramic and Composite Materials Research Group (CERMAT), Federal University of Santa Catarina (UFSC), Campus Trindade, Florianópolis/SC, Brazil

^bCMEMS-UMinho, University of Minho, Campus de Azurém, 4800-058 Guimarães, Portugal

^cSchool of Dentistry (DODT), Post-Graduation Program in Dentistry (PPGO), Federal University of Santa Catarina, Campus Trindade, 88040-900, Florianópolis/SC, Brazil

^dDepartment of Biomaterials and Biomimetics, New York University College of Dentistry, New York University, New York, USA

Abstract

The purpose of this study was to evaluate the biaxial flexural stresses in classic bilayered and in graded zirconia-feldspathic porcelain composites. A finite element method and an analytical model were used to simulate the piston-on-ring test and to predict the biaxial stress distributions across the thickness of the bilayer and graded zirconia-feldspathic porcelain discs. An axisymmetric model and a flexure formula of Hsueh et al. were used in the FEM and analytical analysis, respectively. Four porcelain thicknesses were tested in the bilayered discs. In graded discs, continuous and stepwise transitions from the bottom zirconia layer to the top porcelain layer were studied. The resulting stresses across the thickness, measured along the central axis of the disc, for the bilayered and graded discs were compared. In bilayered discs, the maximum tensile stress decreased while the stress mismatch (at the interface) increased with the porcelain layer thickness. The optimized balance between both variables is achieved for a porcelain thickness ratio in the range of 0.30–0.35. In graded discs, the highest tensile stresses were registered for porcelain rich interlayers ($p=0.25$) whereas the zirconia rich ones ($p=8$) yield the lowest tensile stresses. In addition, the maximum stresses in a graded structure can be tailored by altering compositional gradients. A decrease in maximum stresses with increasing values of p (a scaling exponent in the power law function) was observed. Our findings showed a good agreement between the analytical and simulated models, particularly in the tensile region of the disc. Graded zirconia-feldspathic porcelain composites exhibited a more favourable stress distribution relative to conventional bilayered systems. This fact can significantly impact the clinical performance of zirconia-feldspathic porcelain prostheses, namely reducing the fracture incidence of zirconia and the chipping and delamination of porcelain.

*Corresponding author at: CMEMS - Center for MicroElectroMechanical Systems, University of Minho, Campus de Azurém 4800-058 Guimarães, Portugal. Tel.: +351253510220; fax: +351253516007. brunohenriques@dem.uminho.pt (B. Henriques).

Keywords

Biaxial strength; functionally graded ceramic; zirconia; multilayer

1. Introduction

Dental restorations have two main requirements: adequate strength and good aesthetic. Feldspathic porcelain is widely used as dental material due to its aesthetic. But it has low strength and toughness, accordingly, it is unable to withstand high tensile stresses [1]. Therefore, it is necessary to use a stronger material to support porcelain, increasing the overall strength of the restoration [2]. Due to its high strength, fracture toughness, good aesthetics and biocompatibility, zirconia has been the material of choice for frameworks in all-ceramic dental restorations [2,3]. The feldspathic porcelain is fired onto the zirconia framework at high temperature, and residual thermal stresses are formed at the materials interface upon cooling to room temperature, due to the mismatch of thermal expansion coefficients between the two materials [4,5]. At the same time, when the restoration is subjected to occlusion loading, the mismatch of elastic properties between the two materials favours the formation of deleterious stress fields at the interface that can lead to crack formation, porcelain chipping and ultimately catastrophic failure of the prosthesis [5,6]. To overcome the problems related to thermal and mechanical mismatch between the different materials, several solutions based on a gradation of properties across the two materials have been proposed for dental restorations [7–13]. Studies on the mechanical properties of graded ceramic beams have shown superior load-bearing capacity and improved damage resistance [10,11,14,15]. Enhanced bond strength resistance was also reported for graded restorative systems [7,8,16]. Tsukada et al. showed the feasibility of the production of zirconia/feldspathic porcelain functionally graded materials by spark plasma sintering [12].

Uniaxial tests (e.g. three or four point bending tests) and biaxial tests (e.g. piston-on-three-balls and piston-on-ring tests) are the standard methods to evaluate the flexural strength of ceramics. One problem of uniaxial test is the sensitivity to flaws along the sample edges, resulting in large variations in the strength data recorded [17]. However, in a biaxial test, the multiaxial stress state is created near the center of the specimen and edge failures are usually eliminated, resulting in a more accurate estimate of strength [18]. Besides, restorative materials are usually subjected to a multiaxial loading in clinical situations, thus the biaxial data are more useful for the material design [19]. In biaxial tests, the sample, generally a disc, is supported on its lower face and a load is applied on its upper face. The support can have several configurations, however the most used are rigid balls or ring. The force can be applied by a ball, a ring or a piston [20]. ISO 6872:2015 [21] is the international standard that describes the biaxial flexure test using “piston-on-three-balls”. However, its formulae are based on “piston-on-ring” test.

The objective of this study was to evaluate the mechanical behaviour of a compositionally graded zirconia-feldspathic porcelain disc and compare it with the classic situation, where a sharp interface exists between the two materials. The gradation of properties across the volume of the material can be continuous or stepwise. Because a continuous variation in the

volume fraction throughout the graded region is more difficult to be obtained [22], this work also analysed the stepwise transition where the graded region was considered to have a finite number of layers with varying thickness, each layer with constant volume fraction of the two materials and, therefore, constant properties.

Finite elements method (FEM) was used to simulate the stress state in a “piston-on-ring” biaxial test for all specimen configurations. Several different gradation profiles were simulated in discs with continuous and stepwise variation of the graded interlayer. For the classic situation, the influence of the layer thickness in the stress state was also evaluated. To verify the accuracy of our FEM model, the results were compared with an analytical solution proposed by Hsueh et al. [19,23,24].

2. Materials and methods

2.1. Materials properties and model configuration

For the analysis of the classic situation, with a sharp interface between zirconia and feldspathic porcelain, a disc consisting two layers with 1 mm each was considered. The top layer was made of monolithic feldspathic porcelain and the bottom one contained pure zirconia (Y-TZP). Additionally, simulations considering the porcelain layer thickness as 0.3 mm, 0.6 mm, 0.9 mm while holding the bilayer thickness constant were also conducted (Fig. 1).

For the graded material, two approaches were considered, a continuous and a stepwise gradation between the two base materials. In the first case, continuous gradation, three layers were considered, where the top and bottom layers were monolithic feldspathic porcelain and zirconia, respectively, and the middle layer varied its composition continuously from zirconia to feldspathic porcelain.

In the stepwise gradation, each disc contained seven layers, each one made of constant composition. The top and the bottom layers were still monolithic feldspathic porcelain and zirconia, respectively, and had a constant thickness (0.2mm). The five intermediate layers were made of a feldspathic porcelain and zirconia mixture, having constant volume fraction of porcelain (0.1, 0.3, 0.5, 0.7 and 0.9, from the bottom to top layer, respectively) and varying thickness. In order to calculate the thickness of each intermediate layer, first it is considered a continuous change in the volume fraction of porcelain along the thickness. This change is represented by a power law function:

$$V_p = \left(\frac{z}{t}\right)^p \quad (1)$$

where V_p is the volume fraction of porcelain, z is the distance from the bottom (pure zirconia) and t is the thickness of the graded region. For different values of p , the concentration of zirconia and porcelain along the thickness changes as shown in Fig. 2. To calculate the thickness of each layer, first the values of z/t for a given value of p was calculated for the corresponding values of volume fraction of porcelain of 0.0, 0.2, 0.4, 0.8

and 1.0. These values were used to calculate the thickness of each layer as shown in Fig. 3. In order to evaluate the influence of the composition in the graded region, different values of p were used.

The mechanical properties of intermediate layers, such as Young's modulus, Poisson's ratio and density, were calculated by Voigt's rule of the mixtures:

$$P_i = P_z V_z + P_p V_p \quad (2)$$

where P_i is the property of the i th layer calculated by Voigt's rule of mixtures, P_z and P_p are the properties of the zirconia and porcelain placed on the top and bottom layers, respectively. V_z and V_p are the volume fraction of zirconia and porcelain in the composite. The properties of the base materials (zirconia and feldspathic porcelain) were obtained from the study of Zhang et al. [25].

2.2. Piston-on-ring test

The piston-on-ring test consists of a disc supported by a rigid ring at the inferior face. A piston applies a perpendicular force P on the top of the disc. In this study, all tests were performed with the zirconia layer positioned at the tensile surface. The applied force generates a biaxial moment throughout the disc thickness. As expected, the highest stresses are located along the central axis (z -axis) of the disc ($r=0$), therefore this study was focused on this position. A schematic drawing of a piston-on-ring test is shown in Fig. 4. The disc has a radius R , the supporting ring has a radius a , and the loading piston at the centre of the disc has a radius c .

In this work, the bilayered and stepwise graded discs were divided in several bonded layers, each one with different composition and, therefore, different properties. The disc consists of n layers of individual thickness t_i , where i is the layer number. Layer 1 (zirconia) is located at the bottom of the disc, and layer n (porcelain) is at the top. The interface between the i th and $i+1$ th layers is located at $z=h_i$. The bottom of the disc is located at $z=h_0=0$ and the top is located at $z=h_n$.

2.3. Hsueh's equation

ISO 6872 allows to calculate the biaxial flexure strength only for monolayered discs. However, an analytical solution was proposed by Hsueh et al. [19,23,24] to calculate the stress distribution in multilayered discs. Hsueh et al. formula is derived from the ISO 6872 formulae and presents good accuracy compared with simulated models for trilayered systems [23]. The stress moment in a multilayer disc is described by:

$$\sigma_i = \frac{E_i(z-z^*)M}{(1-\nu_i)(1+\nu_{ave})D^*} \quad (3)$$

where E_i and ν_i are the Young's modulus and the Poisson ratio of the i th layer, M is the biaxial bending moment per unit length, z^* is the position of the neutral plane, D^* is the

flexural rigidity and ν_{ave} is the average Poisson's ratio. E_i and ν_i are calculated by Eq. (2), and the others variables are given by:

$$z^* = \frac{\sum_{i=1}^n \left(\frac{E_i t_i}{1-\nu_i} \right) \left(h_{i-1} + \frac{t_i}{2} \right)}{\sum_{i=1}^n \frac{E_i t_i}{1-\nu_i^2}} \quad (4)$$

$$D^* = \sum_{i=1}^n \frac{E_i t_i}{1-\nu_i^2} \left[h_{i-1}^2 + h_{i-1} t_i + \frac{t_i^2}{3} - \left(h_{i-1} + \frac{t_i}{2} \right) z^* \right] \quad (5)$$

$$\nu_{ave} = \frac{1}{h_n} \sum_{i=1}^n \nu_i t_i \quad (6)$$

$$M = \frac{-P}{8\pi} \left\{ (1+\nu_{ave}) \left(1+2\ln \frac{a}{c} \right) + (1-\nu_{ave}) \left[\left(1-\frac{c^2}{2a^2} \right) \frac{a^2}{R^2} \right] \right\} \quad (7)$$

The variables R , a and c are geometrical and they are shown in Fig. 4. For $n=1$ (only one layer), Hsueh et al. formula is reduced to the ISO 6872 monolayered disc formula. Therefore, the formula can be used to calculate the stress moment for both monolayered and multi-layered discs.

2.4. Finite element method

Finite element method was used to simulate the stress distribution in the piston-on-ring test. A two dimensional axisymmetric model was used to simplify the calculations. The simulations were carried out with the commercial software Comsol Multiphysics v4.3. A constant force is applied at the superior edge of the piston, which then transfer the force to the disc. The supporting ring was fully constrained, and the piston movement was restricted to move only in the vertical axis. All layers were considered to remain bonded during the simulation. A fine mesh with free triangular elements, with maximum size of 0.05 mm, was used. The elements were refined near the region where the stress was the highest, i.e. in the region near the z-axis, in a way that each layer had 20 elements at its edge, except layers smaller than 0.1 mm, which had 10 elements. A mesh refinement study was performed to ensure the accuracy of the simulated results. Using extremely fine mesh was necessary to avoid singularities in the model. In this study, the friction between the disc, the supporting ring and the piston was ignored.

3. Results

3.1. Classic situation

The bilayered discs were 2 mm thick and had radius $R=7$ mm. The loading piston had radius $c=0.075$ mm, and the ring had radius $a=6$ mm. The force applied by the piston was considered 1000 N. The top layer was feldspathic porcelain ($E = 70\text{GPa}$ and $\nu = 0.21$) and the bottom layer was zirconia ($E = 210\text{GPa}$ and $\nu = 0.33$). Four different conditions were simulated, changing the thickness of the porcelain and zirconia layers. Porcelain layer thickness of 0.3, 0.6, 0.9 and 1 mm were simulated. Fig. 5 shows the stress distribution along the thickness in the centre of the disc for the FE model (a) and for the analytical model (b). In both cases, the highest tensile stresses occurred at the bottom of the disc that has greater porcelain thickness.

The values of maximum tensile stress within the sample and the stress mismatch measured at the interface between the porcelain and zirconia are shown in Table 1. The sample with 0.3 mm porcelain layer showed the lowest maximum stress but the highest stress mismatch. Results show that maximum tensile stress decreased when the porcelain thickness increased and that the stress mismatch varied in the opposite way. The values of the simulated model agree well with the analytical model. The maximum deviation between the simulated and the analytical results for maximum tensile stresses was less than 5%.

Fig. 6 shows the variation of the simulated maximum tensile stresses and stress mismatch against the porcelain thickness ratio t_p/t_T , where t_p is porcelain thickness and t_T is the total thickness. It reveals that the optimized balance between the two stresses is achieved for a porcelain thickness ratio in the range of 0.30–0.35.

3.2. Graded Material

The top layer, made of feldspathic porcelain ($E = 70\text{GPa}$ and $\nu = 0.21$), and the bottom layer, made of zirconia ($E = 210\text{GPa}$ and $\nu = 0.33$), were both 0.2 mm thick. The Young's moduli and the Poisson's ratios were estimated by Voigt's rule of mixtures. Their values for different porcelain volume fractions on the composite are presented in Table 2. In the stepwise graded discs the porcelain volume fractions considered for each of the five intermediate layers were 0.1, 0.3, 0.5, 0.7 and 0.9. The force applied by the piston was also considered 1000 N. Conditions for $p=0.25, 0.5, 1, 2, 4$ and 8 were simulated and calculated analytically. Table 3 shows the layer thicknesses for each value of p . Layer 2 is the first graded layer, near the bottom zirconia layer, with 90% of zirconia and 10% of porcelain (vol.%), and layer 5 is the graded layer near the top porcelain layer, with 90% of porcelain and 10% of zirconia.

Fig. 7(a–c) shows the simulated and analytical stress distribution throughout the disc centre. Maximum tensile stresses were measured at the bottom surface of the disc, regardless of the value of p . The highest and lowest values, taken from the continuous model, were registered for $p=0.25$ and $p=8$, with 678 MPa and 514 MPa, respectively. Fig. 8 shows a plot of the maximum tensile stresses measured in the disc against the p values for the three models. It is seen a drop in maximum stresses with increasing p values. The simulated results agree well

with the analytical model, with a maximum deviation of 5% between them observed for $p=8$, where the maximum deviation between the results is registered.

4. Discussion

The influence of the feldspathic porcelain thickness on the biaxial flexural strength of classic bilayered zirconia-feldspathic porcelain discs has been presented in this study. The study of bilayered systems was conducted in order to allow a comparison of results with those obtained for graded discs. Discs were tested with zirconia being at the bottom layer (tensile surface) and porcelain at the top layer (compressive surface). This configuration was selected based on the in-service configuration of all-ceramic restorations, where the zirconia substructure is veneered by feldspathic porcelain.

The porcelain thickness showed to have significant impact on the stress distribution of the zirconia-feldspathic porcelain discs. Maximum tensile stress increased by 24% and the stress mismatch at the interface was reduced by 53%, when the porcelain thickness was increased from 0.3mm to 1mm. The maximum tensile stress occurred at the bottom surface of the disc. Huang et al. showed that if zirconia was on top and porcelain at the bottom of the disc the maximum tensile stress could be shifted to the interface between the materials [23].

Regarding the graded discs, results showed that the gradation profile given by the exponent p in Eq. (1) can be used to tailor the location, orientation and magnitude of stresses within the graded discs. Discs with higher content of zirconia phase (higher p values) in the graded region presented smaller maximum stress than the ones with smaller values of p . The maximum tensile stress in the disc is increased by 28% when the content of the graded region switches from zirconia rich ($p=8$) to porcelain rich ($p=0.25$). The benefits of the gradients are evident and it became especially important for discs with small porcelain thickness. As example, the maximum tensile stress is equivalent in graded discs with small porcelain thickness ($p=8$) and in bilayered disc with porcelain thickness of 0.3 mm, 530 MPa and 505.3 MPa, respectively. However, the huge stress mismatch at the interface of bilayered discs is replaced by a smooth profile in stress distribution of graded discs.

It is interesting to note that for p values greater than 1 the maximum compressive stress is deflected to the interior of the disc and its difference to the stress measured at the end of the graded interlayer (interface between the graded interlayer and the porcelain layer) increases for increasing p values. The $p=8$ produced the lowest stress value at the upper end of the graded interlayer, which in turn, resulted in the lowest compressive stress value on the top surface of the disc. Similar behaviour was reported by Zhang et al. for graded sandwich beams [11]. However, because of the symmetrical gradation relative to neutral axis of the beam, the deflection of maximum stresses occurred both on top and bottom of the beam, i.e. in the compressive and tensile sides, respectively. Instead, this work focused on the study of different transition profiles (different allocation of materials) in the graded interlayer, given by the different p values in Eq.(1), across the thickness of a disc.

The results show good agreement with the analytical model, except in the region under compression, near the loading piston. This is because the analytical model does not account

for the contact stress under the piston in the calculations and considers only the stress due to the bending moment of the disc. Therefore, while in the analytical model the stresses are linear through the thickness of each layer, in the simulated model, there is a distinct curve in the stress near the top of the disc due to the contact stress between the piston and the disc. Similar findings were reported by [23].

In this work, an arbitrary number ($n=5$) of layers were selected for the stepwise transition in the graded layer. A higher number of layers could be selected towards an approximation to a continuous transition. Nevertheless, results have shown that stresses are comparable to that of continuous transition (Fig. 7 and Fig. 8). The difference is the alternating tensile and compressive stresses in the mixture layers. The stresses also reverse in sign at the interfaces. These stresses need to be controlled because they can lead to delamination at the interfaces if the bonding is not strong after multilayer fabrication. Increasing the number of layers can contribute to decrease the stress mismatch at the interfaces. At the same time it increases the complexity of the fabrication of the structure, and a trade-off between fabrication parameters and stress design must be balanced.

The choice of a particular graded structure is highly dependent on the processing technique. The production of continuous graded structures can be obtained with relative ease by controlling the feeding of powders of two materials in plasma spray deposition, for instance. High expectations are placed upon the development of selective laser sintering/melting for the solid freeform fabrication of multi-material ceramic components [26]. On the other hand, the fabrication of multi-layered parts can be conducted economically using techniques such as tape casting, dip coating, and hot pressing [27].

Another alternative for producing graded zirconia-feldspathic porcelain structures is the fabrication of zirconia structures with controlled porosity gradients that is afterwards infiltrated with feldspathic porcelain for achieving the structural strength. Using the same method, feldspathic porcelain can be replaced by other resorbable ceramics, polymers or composite materials for other biomedical applications (e.g. hip prostheses, scaffolds, etc.).

Thermal residual stresses are formed on bilayered or multilayered ceramics upon cooling from high sintering temperatures due to thermal expansion mismatches between the different constituent materials. These stresses were not incorporated in the model used in this study, although they would influence the results in a real experiment. Materials having gradation in composition (FGMs) are specially suited to cope with thermal stresses, promoting a reduction in stresses magnitude and smoothing their profiles [4,9,13,28].

5. Conclusion

In this work, an analytical method and a finite element method were used to evaluate the stress distribution in bilayered and graded discs tested in biaxial flexural tests. The following conclusions can be drawn:

The thickness of porcelain veneer has a significant influence on the maximum tensile stress and stress mismatch at the interface in bilayered feldspathic porcelain-zirconia discs.

Thinner porcelain layers yield lower maximum tensile stresses but greater stress mismatch at the zirconia-feldspathic porcelain interface.

The optimized thickness ratio in terms of low maximum stress and low stress mismatch for zirconia-feldspathic porcelain bilayered discs has been determined and is in the range of 0.30 – 0.35.

The gradation in composition across the thickness of the discs is responsible for a reduction in the magnitude of tensile stress and stress mismatch in zirconia-feldspathic porcelain discs.

A stepwise transition provides a good approximation to continuous transition, reducing the maximum tensile stress and imparting a favourable redistribution of stresses in the disc.

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Fig. 1. Schematic of the classic bilayered (a) and graded (b,c) zirconia-feldspathic porcelain systems.

Fig. 2. Variation in the volume fraction of porcelain throughout the graded region for different values of the scaling exponent p in Eq.(1).

Fig. 3.
Procedures to calculate the layers thickness of the graded region for $p=4$.

Fig. 4. Diagram of piston-on-ring biaxial test. P is the applied force by the piston and t is the thickness of each layer.

Fig. 5. Stress distribution in a biaxial test along the z-axis at the disc centre for a bilayered sample. Results for FEM simulation (a) and the analytical model (b).

Fig. 6. Variation of the simulated maximum tensile stresses and stress mismatch against the thickness ratio t_p/t_T (t_p : porcelain thickness; t_T : total thickness). Note the different stress ranges shown in the y-axis for maximum tensile stress and stress mismatch at the interface.

Fig. 7. Stress distribution throughout the disc thickness for a biaxial test in a FGM. Results for the simulated models: continuous transition (a) and stepwise transition (b); and analytical model (c).

Fig. 8. Maximum tensile stress as function of the scaling exponent p in Eq. (1). Maximum difference between simulated and analytical results was registered for $p=8$ and was ~5%.

Table 1

Maximum stress and stress mismatch in the interface between layers for a bilayer disc.

	0.3 mm	0.6 mm	0.9 mm	1 mm
Maximum stress (simulated)	505.3 MPa	574.1 MPa	618.6 MPa	627.7 MPa
Maximum stress (analytical)	520.6 MPa	592.5 MPa	620.0 MPa	619.7 MPa
Stress mismatch (simulated)	301.2 MPa	264.3 MPa	147.8 MPa	141.1 MPa
Stress mismatch (analytical)	336.2 MPa	306.8 MPa	206.1 MPa	158.3 MPa

Table 2

Estimated values of the mechanical properties of zirconia-feldspathic porcelain composites with different feldspathic porcelain contents, calculated by Eq.(2)

Porcelain content (vol.%)	Young's modulus (GPa)	Poisson's ratio	Density (kg/m ³)
10	196	0.32	5730
30	168	0.29	4990
50	140	0.27	425
70	112	0.25	3510
90	84	0.22	2770

Table 3

Thickness of each of the 5 layers of the graded transition determined for different values of p in Eq. (1).

	$p=0.25$	$p=0.5$	$p=1$	$p=2$	$p=4$	$p=8$
Layer 2	0.002 mm	0.064 mm	0.320 mm	0.715 mm	1.070 mm	1.310 mm
Layer 3	0.038 mm	0.192 mm	0.320 mm	0.296 mm	0.202 mm	0.119 mm
Layer 4	0.166 mm	0.320 mm	0.320 mm	0.227 mm	0.135 mm	0.074 mm
Layer 5	0.448 mm	0.448 mm	0.320 mm	0.192 mm	0.105 mm	0.055 mm
Layer 6	0.944 mm	0.576 mm	0.320 mm	0.169 mm	0.087 mm	0.044 mm