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Influence of Interlayer Design on Residual Thermal Stresses in Trilayered and Graded All-Ceramic Restorations

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Abstract

Residual thermal stresses are formed in dental restorations during cooling from high temperature processing. The aim of this study was to evaluate the influence of constructive design variables (composition and interlayer thickness) on residual stresses in alumina- and zirconia-graded restorations. Restorations' real-like cooling conditions were simulated using finite elements method and temperature-dependent material properties were used. Three different designs were evaluated: a bilayered restoration (sharp transition between materials); a trilayered restoration with a homogenous interlayer between core and veneer; and a trilayered restoration with a graded interlayer. The interlayer thickness and composition were varied. Zirconia restorations presented overall higher thermal stress values than alumina ones. Thermal stresses were significantly reduced by the presence of a homogeneous interlayer. The composition of the interlayer showed great influence on the thermal stresses, with the best results for homogeneous interlayers being observed for porcelain contents in the composite ranging between 30%-50% (vol.%), for both alumina and zirconia restorations. The interlayer's thickness showed a minor contribution in the thermal stress reduction. The graded interlayer showed an optimized reduction in restorations' thermal stresses. The use of graded interlayer, favoring enhanced thermal stress distributions and lower magnitude is expected to reduce the risk of catastrophic failure.

Keywords

Graded ceramics; feldspar-basedporcelain; alumina; zirconia; thermal residual stresses

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1. Introduction

Dental restorations must simultaneously meet several requirements to display a good performance. The main requirements are biocompatibility, strength, corrosion resistance and good aesthetic. Because mono-layered restorations can hardly address all these requirements, layered multimaterial systems have been used in dental prosthesis. A strong framework veneered with an aesthetic material generally composes a dental restoration. Zirconia and alumina have been used in all-ceramic restorations as framework materials due to their biocompability, high strength and aesthetics [1–3]. A proprietary feldspar-based porcelain is thus used as veneer to mimic the teeth appearance.

Failure types typically reported for alumina-based restorations are the core and the veneering ceramics fracture, while for the zirconia-based restorations is the chipping of the veneering ceramics [4–7]. Alumina crowns tend to present a catastrophic fracture with the cracks propagating through the core [7–9]. In zirconia crowns, chipping in the veneer layer prevails over other failure types, with cracks growing parallel to the interface [10–13].

The presence or development of tensile residual stresses formed in multimaterial prostheses due to the thermal contraction mismatch between the core and veneering ceramics has been identified as one of the major causes of catastrophic failure [14–20]. The brittle nature of ceramics makes them inadequate to handle the high tensile stresses from functional loading. This issue gets special relevance if laboratories combine ceramics from different commercial systems, eventually jeopardizing the restoration. Several factors influence the formation of thermal residual stresses in restorations: materials, design and cooling rate. Zhang et al. [21] showed that the formation of thermal stresses in zirconia restorations is more sensitive to changes in design and fabrication variables than the alumina restorations. The cooling rate has been shown to play a critical role in crack initiation and propagation in bilayered ceramic structures, with fast cooling leading to thermal fracture [21].

The minimization of thermal residual stresses developed during fabrication is therefore of high priority in order to reduce the incidence of veneer ceramic surface crumbling and chipping in all ceramic dental prostheses.

Functionally Graded Materials (FGMs) can be an answer to the thermal stress problems [22,23] consisting of a gradual change in the volume fractions of constituents from one location to the other in a component. The FGMs were first applied in minimizing thermal stresses and increasing thermal shock resistance of blades in gas turbine engines, with great success [22,24]. The philosophy was rapidly adapted by engineers to other fields of activity such as optics, nuclear energy, engineering, electronics, biomaterials, among others. In this way, several solutions based on a gradation of properties across the two materials (core and veneer) have been proposed for dental restorations in order to address the problems related to the thermal and mechanical mismatches [25–32]. While several studies have pointed graded prosthetic systems as displaying superior load-bearing capacity, improved damage resistance [31,32] and enhanced bond strength resistance [33], to the author's best knowledge, little work has been reported on modeling thermal stresses in functionally graded restorations [25,26,30]

The design parameters of layered structure, such as composition and thickness of the layers, might change the stress magnitude and the location of maximum stress, hence the proper optimization of such parameters is important to minimize residual thermal stress in critical locations. Besides decreasing tensile thermal stresses, studies have shown that the proper FGM design can also increase compressive stresses, which can lead to enhanced fatigue life of the component [34].

The aim of this study was to evaluate the thermal residual stress variations for different graded ceramic dental prosthesis designs, using finite elements method (FEM). Three different core-veneer interface configurations were simulated: the traditional bilayered restoration; a trilayered restoration, with a homogeneous composite interlayer between the framework and the veneer; and a graded restoration, with a compositionally graded interlayer between the framework and the veneer. Zirconia and alumina were used as framework materials and interlayers' thickness and composition were also varied.

2. Materials and methods

2.1. Material properties

In this study, zirconia (Y-TZP) and alumina were used as framework materials while feldspar-based porcelain was used as veneering material. The temperature dependent properties of these homogeneous and isotropic materials where adopted from literature [21] and are summarized in Tables 1-3.

The properties of the composite materials (zirconia-porcelain and alumina-porcelain) used in the composite interlayers, as presented ahead in the text, were estimated by Voigt's rule of mixtures, which is given by:

$$P_i = P_f V_f + P_v V_v \quad (1)$$

where P_i is the calculated property value of the intermediate layer, P_f and P_V are the material property values of the framework and veneer, and V_f and V_V are the volume fraction of the materials in the composite. Figure 1 shows the values of CTE and Young's Modulus as a function of temperature and composition (feldspar-based porcelain content in the composite) for zirconia-porcelain and alumina-porcelain composites.

2.2. Models and finite method analysis

A restoration (crown) was modeled with two or three layers which simulates its three components: the framework, the veneer and the interlayer with intermediate properties between them. The residual thermal stress analysis after the cooling process was performed for three types of restoration (crown) designs: a bilayered restoration with a sharp transition between the framework and the veneer; a trilayered restoration with a composite interlayer of constant composition; and a trilayered restoration with a compositionally stepwise gradation. Figure 2 illustrates the different crown designs.

The classic bilayered restoration is comprised of a zirconia (Y-TZP) (or alumina) framework veneered with a proprietary feldspar-based porcelain. The framework has a constant thickness of 0.67 mm while the porcelain veneer is 1.7 mm thick at the central fossa (r=0) and a varying thickness over the restoration outline.

The trilayered restoration with interlayer of constant composition has a zirconia or alumina framework (thickness of 0.67 mm), a composite interlayer between the framework and the veneer, and a veneering porcelain. Five interlayer compositions and three interlayer thicknesses were considered. The composition of the interlayer were made of a feldspar-based porcelain and zirconia mixture (or feldspar-based porcelain and alumina mixture), having constant volume fraction of porcelain (10%, 30%, 50%, 70% and 90%). The interlayer thicknesses tested were 0.3 mm, 0.5 mm and 0.75 mm.

The graded restorations comprised of a zirconia (or alumina) framework, an interlayer with a gradient of composition between that of the framework and that of the veneer, and a porcelain veneer. The geometry was the same as used in the restoration previously described, although with a stepwise graded interlayer. In the stepwise gradation, the interlayer was divided into 10 smaller and equally spaced layers, each with constant volume fraction of porcelain (5%, 15%, 25%, 35%, 45%, 55%, 65%, 75%, 85% and 95%, from the bottom to top layer, respectively) in the zirconia-porcelain and alumina-porcelain mixtures. Simulations were performed for graded interlayer thicknesses of 0.3 mm, 0.5 mm and 0.75 mm.

In order to increase the accuracy of the simulation, temperature-dependent materials were adopted in the model. Two different porcelains were used, each optimized to match the CTE of zirconia or alumina (VITA VM9 and VM7, respectively).

Figure 3 illustrates the evolution of CTE and Young's modulus across dental restorations with the different configurations used in this paper.

In this work, a 3D molar tooth model was used (Figure 2). The FEA was conducted using the commercial finite element software COMSOL Multiphysics (Comsol Inc, Los Angeles, USA) adapting triangular elements. In order to simplify the study, the 3D computational model of the crow was sectioned to a 2D-axisymmetric model (Zhang et al., 2010, 2012) (Figure 2). At the beginning of the simulation, the restoration is stress free and its temperature is uniform at 773.15 K (500°C). Then the temperature on the restoration walls decreases at constant cooling rate from the initial temperature to 273.15 K (20°C) during 950 seconds, i.e. with a constant cooling rate of 0.5 K/s. Slow cooling is recommended by the manufacturer to reduce the amount of residual stresses that generate in the veneer due to temperature gradients during the cooling period of the firing cycle.

Since the temperature on the walls is known, only conductive heat transfer was considered on the model. Other thermal phenomena, such as convection and radiation, were neglected on this study. Fourier's law (Equation 1) was used to calculate the heat conduction on the samples, which gives the governing equation for pure conductive heat transfer used on this model (Equation 2). In these equations, ρ is the density, C_p is the specific heat, T the absolute temperature, q is the heat flux by conduction and Q contains other heat sources.

$$q=-k\frac{\partial T}{\partial x} \quad (1)$$

$$\rho C_p\frac{\partial T}{\partial t}+\nabla(-k\nabla T)=Q \quad (2)$$

The residual thermal stresses were calculated using the thermal strain due to the temperature change in the samples. The thermal strain depends on the coefficient of thermal expansion (CTE) α, the strain reference temperature (T_{ref}), i.e, the temperature which the model is stress free, and the temperature T, as shown on equation 3.

$$\varepsilon=\alpha(T-T_{\mathrm{ref}}) \quad (3)$$

The layers were considered fully bonded during the simulation. A free triangular mesh was used due to the complex geometry, mainly at stress concentration points. The maximum size of each element was 0.437 mm, resulting in the total amount of approximately 8500 to 12000 elements for each model. The convergence analysis was performed in order to examine the sensitivity of the results to the size of the mesh. Differences in maximum principle stresses were found to be lower than 3% for consecutive mesh refinements.

3. Results

The simulations showed three different stress raisers spots: at the inner part of the framework; at the interface between the framework and the interlayer; and at the interface between the interlayer and the veneer as shown in Figure 4. The latter is located at the intermediate layer while the other two spots are at the framework layer. This paper will analyse the maximum principal stress on these three locations.

3.1. Bilayered restorations (classic restorations)

Table 1 shows the maximum principle stresses obtained for bilayered restorations in two different locations, at the framework/veneer interface and at the inner part of the framework. The zirconia/porcelain restoration presented significantly higher stress than the alumina/porcelain restoration, at both sites of analysis. In the zirconia/porcelain restoration stresses were lower at the framework/veneer (F/V) interface than at the inner part of the framework (F). On the other hand, stresses registered at the alumina/porcelain restoration did not significantly differ between both locations.

3.2. Trilayered restoration with homogeneous interlayer

Figure 5 shows a plot of the maximum principle stresses computed for zirconia and alumina based restorations with composite interlayers of different compositions and thicknesses. It can be seen that stresses are higher in zirconia restorations than in alumina restorations.

Also, increasing the porcelain content in the interlayer increases the stress at the framework (F - inner part) and framework/interlayer (F/I), for both zirconia and alumina, while reducing the stress at the interlayer. For porcelain rich interlayers (porcelain content in excess of 50 vol.%) the stresses did not change significantly with the variation of the interlayer's thickness. On the other hand, for interlayers having lower porcelain content (less than 50 vol.%) the maximum stresses were lower for thicker interlayers.

It is important to point out that the maximum stress at the interlayer (interlayer/veneer interface) decreases by more than 75% (regardless the interlayer's thickness) relative to conventional bilayered zirconia- and alumina-based restorations when the porcelain content in the interlayer is greater 50% (vol.%).

3.3. Trilayered restoration with graded interlayer

Figure 6 shows the maximum principal stresses at the inner part of the framework and at the interface between the framework and the interlayer for all interlayer thicknesses. The results show a slight decrease of the maximum stresses for increasing interlayer's thicknesses, at both stress concentration points.

The maximum stresses measured at the inner part of the framework of the graded restoration did not change significantly relative to those measured in conventional bilayered restorations. However, a great stress reduction was seen at the interface between the framework and the graded interlayer, where a reduction of 32% and 25% was seen in the alumina- and zirconia-based restorations, respectively, with interlayer thickness of 0.75 mm.

Figure 7 summarizes the maximum stresses measured at the interface between framework and interlayers, and at the interface between the interlayer and the veneering porcelain (considered critical locations in the restoration, as explained ahead in the discussion section) for the different configurations of restorations analysed in this work. It can be seen that the graded interlayers is the one that best balances the stresses within the restorations, minimizing their magnitude in both critical locations.

4. Discussion

Among the most common failures of multilayered ceramic restorations are the catastrophic fracture and porcelain chipping [35,36]. This has been attributed to materials' thermal and mechanical mismatch and occurrences come from laboratorial fabrication to in-mouth incidents. Recently developed graded structures have been proposed to address thermal and mechanical coupling in dental restorations with significant improvements in load-bearing capacity, adhesion, wear resistance and aesthetics. [31–33,37]. However, to the authors' best knowledge, no studies have explored the residual thermal stresses in graded ceramic restorations. Henriques et al. [25,26] has addressed that topic in metal-ceramic restorations. Hence, the present study analyses the influence of the constructive design of a dental restoration as regard to the type of material and presence of an interlayer with varying composition (homogeneous and graded) and thickness, on the state of thermal residual stresses.

Results obtained for bilayered systems shows that higher residual stresses are formed in zirconia restorations rather than in alumina restorations, and it is in accordance to other authors' findings [11,38]. This fact is related to the lower thermal conductivity of zirconia, which is approximately 15 times smaller than that of alumina, thus resulting in slower cooling processes of zirconia-based restorations relative to alumina-based restorations. Therefore, high transitional temperature differences throughout the restoration are formed, especially at the thicker and irregular layers and upon fast cooling. The temperature differences created between the outer and the inner part of the restoration introduces high transient thermal gradients within the restoration that results in the formation of higher residual thermal stresses [39,40].

A mismatch of the thermal expansion coefficient (CTE) between the feldspar-based material and the framework material (alumina or zirconia), together with the effect of thermal diffusivity, thermal conductivity (conductive heat transfer), thermal specific heat and density (convective heat trensfer) [39] upon cooling after sintering, are regarded for the formation of transient and residual stresses. Stress intensity is directly proportional to the differences in the CTE of the two materials from the glass transition temperature of porcelain (Tg) to room temperature. In this study, porcelains with compatible CTEs to their coupling materials have been selected. The CTE's mismatch between porcelain and framework material (zirconia or alumina) did not differ significantly, as can be seen in Table 1, Table 2 and Table 3.

Zhang Z et. [21] also showed that zirconia restorations are more sensitive to changes in design (core thickness) and fabrication (heat transfer coefficient) parameters than alumina ones, i.e. more dramatic variations in thermal stresses are expected with small variations of these parameters for zirconia restorations. This was attributed to a higher thermal specific heat and density in zirconia than those in alumina [21]. Zhang Z et al.[39] also showed that the thermal conductivity of a material is more relevant in conduction heat transfer rather than in convective heat transfer. Based on results one may say alumina has better coupling to porcelain than zirconia, evidenced by smaller residual thermal stresses formed during restoration's cooling from porcelain sintering temperature. However, because zirconia has higher flexural strength (about twice as strong as the alumina) it has been shown much higher reliability and therefore more suitability for using as framework material in dental restorations [3], with longer lifetime prediction than alumina and comparable to metal-based restorations [41]. The flexural strength and Weibull modulus of alumina, zirconia and feldspar-base porcelain are listed in Table 5.

It was seen that tensile stresses occur in the framework while porcelain veneer was under compression, with the peak tensile stress being registered at the interface on the framework side (Figure 8). Similar finding was reported elsewhere [25,38]. This finding highlights the interface as a critical region in restorations and supports the evidences, reported elsewhere [11,43], of the interface as a crack nucleation and propagation site. Zhang et al. [11] reported that crack consistently initiated and ran tangentially to the porcelain–zirconia interface within the porcelain and in some samples, propagated completely through the porcelain layer and caused chipping. The fracture failure rate in bilayered restorations may be reduced by increasing the thickness ratio, despite thick framework is expected to compromise the aesthetics by a translucency reduction [38].

The presence of a composite interlayer showed to promote a thermal stress reduction in critical locations such as framework/interlayer interface and interlayer/veneer interface, relative to bilayered systems. This is in accordance to results reported for metal-ceramic restorations using similar interface designs (Henriques et al.). The thermal stresses showed to be sensitive to the materials (as seen before) and to the interlayer design (composition and thickness). Thermal stresses could be reduced up to 35% at the framework/interlayer interface and up to 80% at the interlayer/veneer interface relative to those measured at the framework/veneer interface in bilayered restoration. These thermal stress reductions can account for a decrease in the probability of crack nucleation and growth due to thermal stress, and increase in-service stress that the restoration can stand. High stresses at the interface can also cause delamination if the layers are not bonded properly in the manufacturing process. Thus, the restoration project, besides minimizing overall stresses, should also restrict high stresses at the framework, which must be made with a tough and strong material to withstand the stresses generated by in service use and by the processing. Moderate compressive stress at the surface can be beneficial in ceramics and increase the lifetime. The occurrence of stress reduction was not seen in frameworks with the same extent as seen in other locations of the restoration, especially at the interfaces. However, framework is not seen as critical location due to their significantly higher flexural strength relative to veneering materials. Higher content of porcelain in the interlayer resulted in the increase in maximum stress in the framework. The stress at the interface between the framework and interlayer increases with the increasing porcelain content, because the CTE mismatch between the layers increases. The maximum stress is located at the restoration's center due to its geometry. The radius of curvature creates a stress raiser point.

The graded restoration presented a slightly smaller maximum stress in the inner part of the framework if compared to the trilayered restoration with the same porcelain overall content, which is 50%. Graded structures with lower porcelain content could further decrease the maximum thermal stresses. Besides that, gradient of composition improve the stress distribution, considerably decreasing stress mismatch between layers, for both framework/interlayer and interlayer/veneer interfaces. While the increase in porcelain content in the composition of the homogeneous interlayers showed a tendency of increasing stresses between the interlayer and the framework, and at the same time, decreasing them between the interlayer and the veneer, the graded interlayer produced an optimum output by simultaneously decreasing the thermal stresses at both interfaces. This result can be correlated with studies conducted by Huang el al. 2007, which reported a reduction of 30% in the maximum principal stresses in FGM systems subjected to contact induced deformation.

The presence of a composite interlayer, either graded or homogeneous, has an additional benefit provided by the enhanced fracture toughness relative to the veneering porcelain, making necessary an additional amount of energy for fracture to occur [44–47].

Ten layers were selected for the stepwise transition in the graded layer. However a higher number of layers could be selected to approximate the materials transition to a continuous change, but the fabrication complexity would increase. The stepwise model has been used for FGM's model, since it would correspond to an easier and less expensive laboratorial process. Several routes can be used to achieve a discrete graded region, such as tape casting, dip coating and hot pressing [48]. Ravichandran [49] showed that a stepwise approach having several layers (typically at least 11) presents similar results regarding thermal stress to that of continuously graded structure.

The model used in this study incorporates some simplifications that may be considered as limitations. First, it was assumed a symmetric cooling pattern, which may contrast to eventual asymmetric thermal gradients occurring in real crown cooling. Additionally, a perfect coupling between layers was also assumed, which might be distinct from a real scenario. Also, the simplified 2D axisymmetric model used in this study has obvious limitations, as it might miss specific components and interactions important in real 3D geometry. Finally, current FEA model neglected the viscoelastic behavior of porcelain at the temperature above its Tg. Therefore, the true stress profiles might not be captured accurately. Despite the limitations, this study provides general insights as regard to the influence of multilayers design in the formation of thermal stresses in graded restorations.

5. Conclusion

In this study, thermal residual stresses were evaluated in graded ceramic restorations with different designs. The following conclusions can be drawn:

- Zirconia based restorations present significantly higher residual thermal stresses than alumina based ones.
- The presence of an interlayer can considerably reduce thermal residual stress at the interface between layers and at stress concentration points. Stress magnitude reduction can reach 70%at specific locations (interlayer/veneer interface) and for specific interlayer compositions (~30% - 50% of porcelain content), relative to those measured in bilayered ceramic restorations.
- Both composition and thickness of the interlayer have great influence on residual thermal stresses. The optimum interlayer composition is in the range of 30% - 50% porcelain, which balances the stress in the framework and at the interfaces. Stresses decreases with increasing interlayer thickness, mainly at low porcelain contents.
- The graded restoration showed the best thermal stress distribution, with simultaneously reduced values at the framework and at the interface.
- A beneficial effect with regard to thermal stress reduction was seen in all-ceramic restorations having a homogeneous or graded interlayer, which may lead to a reduction in processing failures (during fabrication) and in-service failures.
- The simplified axisymmetric model used in this study has obvious limitations, as it might miss specific components and interactions important in real 3D geometry. Nevertheless, the model indicates the main trends and compares data for different constructive design of graded ceramic restorations.

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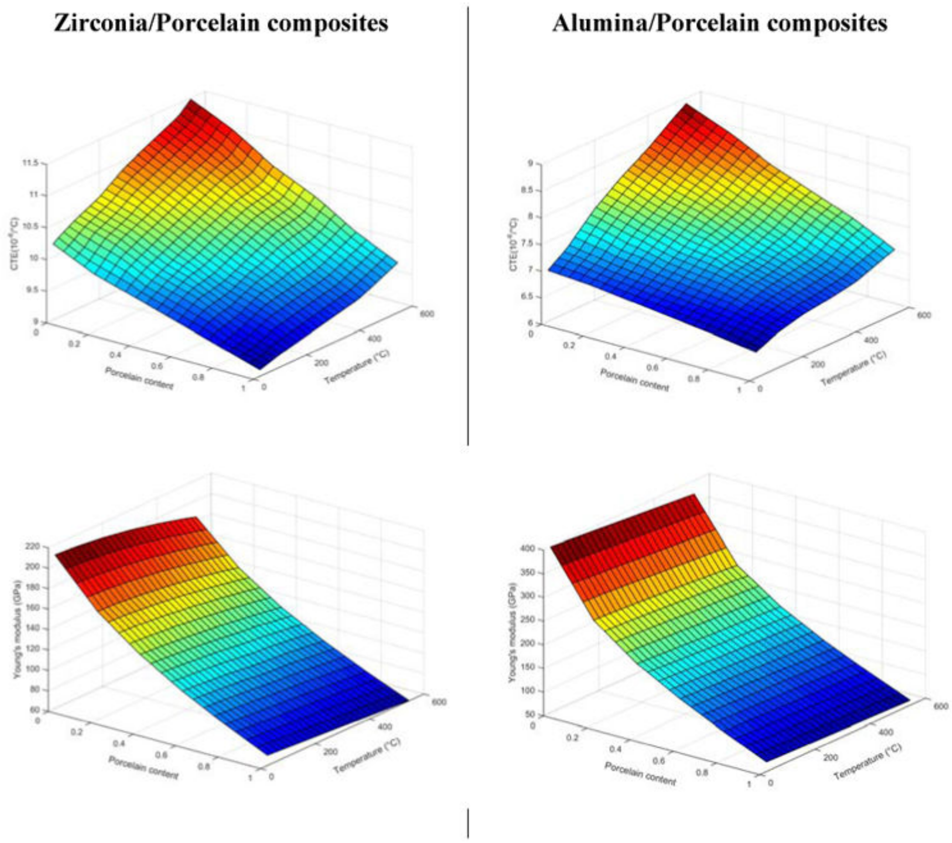

Figure 1.

CTE and Young's modulus of the zirconia/porcelain and alumina/porcelain composites plotted as function of temperature and porcelain content in the mixture.

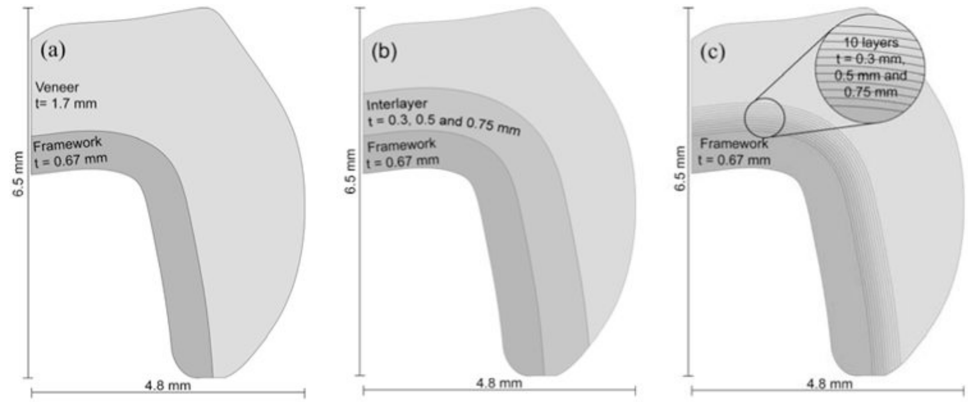

Figure 2.

Modeled restorations with different constructive designs: (a) sharp transition between framework and veneer; (b) interlayer of constant composition (porcelain volume fractions of 10%, 30%, 50%, 70% or 90%) between framework and veneer; and (c) compositionally stepwise graded interlayer between framework and veneer. The graded interlayer comprised 10 thin layers, each with a different volume fraction of porcelain (5%, 15%, 25%, 35%, 45%, 55%, 65%, 75%, 85% and 95%), from the bottom to top layer, respectively.

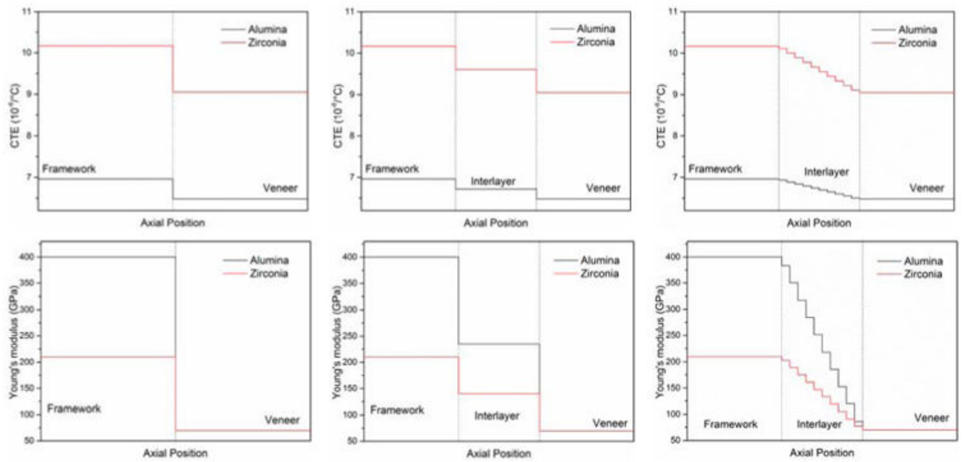

Figure 3.

Evolution of the coefficient of thermal expansion (CTE) and Young's modulus for the alumina/porcelain and zirconia/porcelain restorations with sharp transition, intermediate composite layer and stepwise graded interlayer at room temperature.

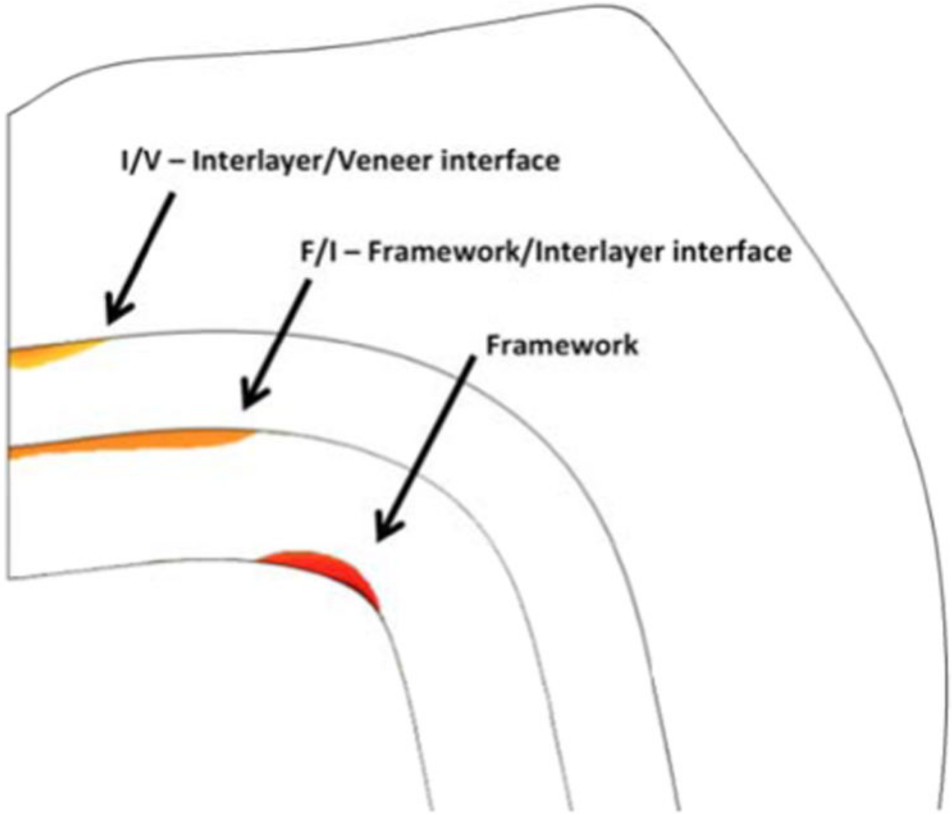

Figure 4.
Stress concentration points: located at the inner part of the framework; at the interface between framework and interlayer (F/V); and at the interface between interlayer and veneer (I/V).

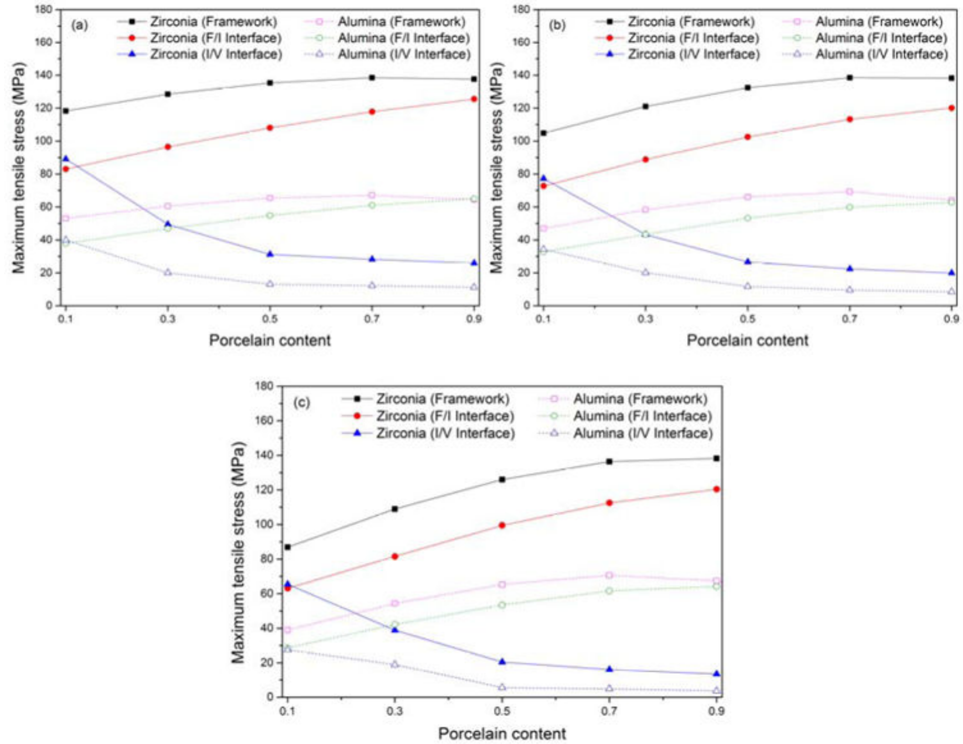

Figure 5.

Maximum stress for restorations with interlayer thickness of 0.3 mm (a), 0.5 mm (b) and 0.75 mm (c) plotted as a function of the porcelain content in the interlayers composition, and analysed in three locations: framework inner part, interface between framework and interlayer (F/I Interface), and interface between interlayer and veneer (I/V Interface).

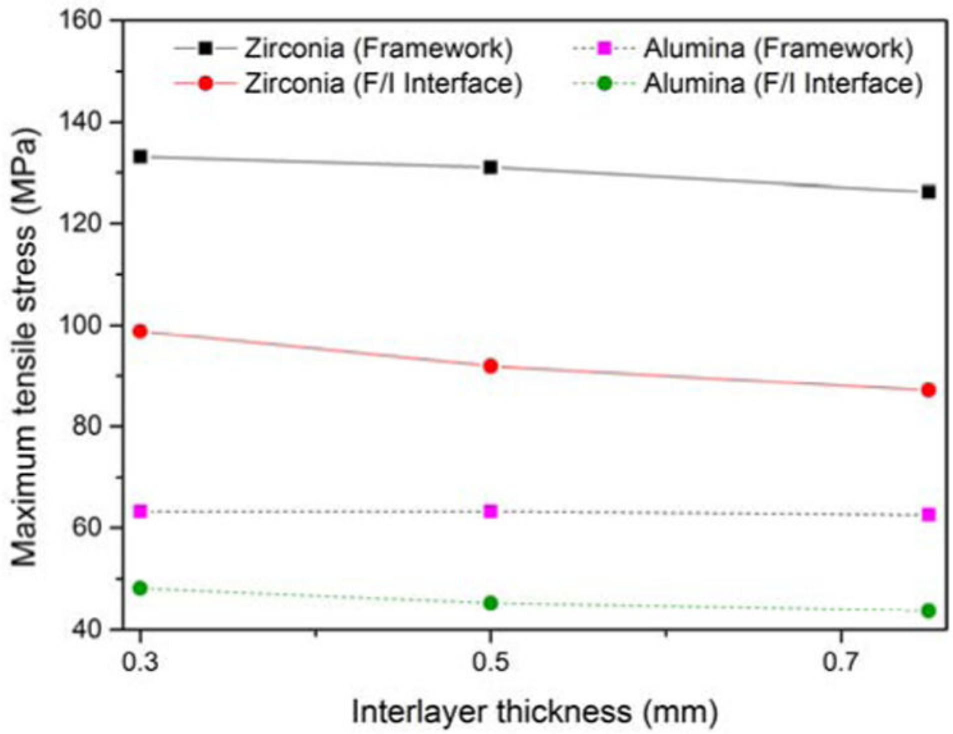

Figure 6.

Maximum stress in the graded restoration for different interlayer thickness at the restoration center (Framework) and at the interface between framework and graded region.

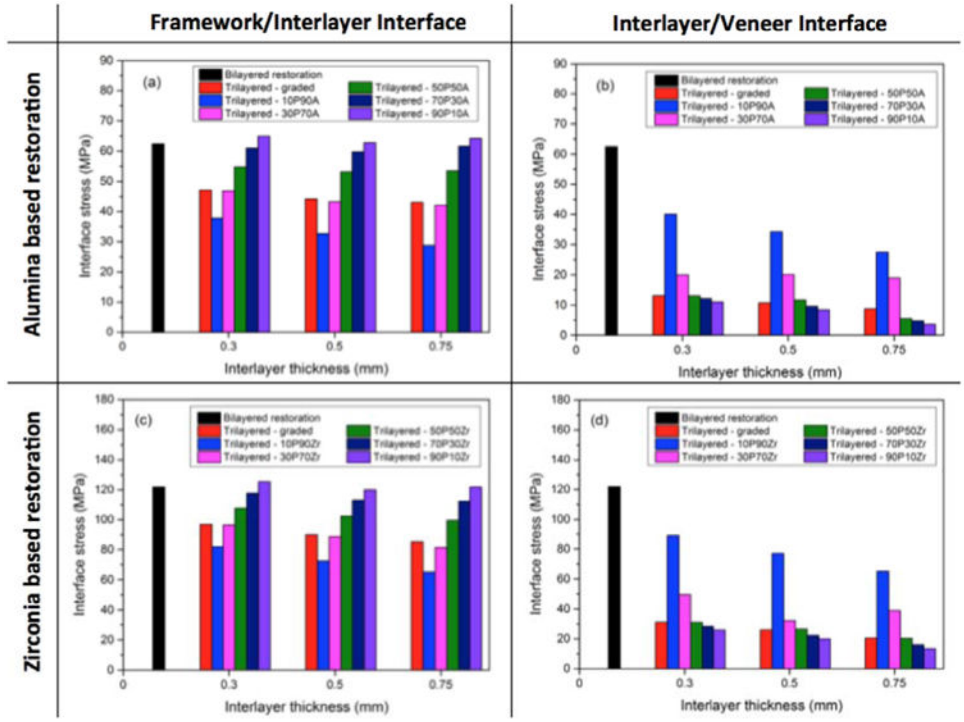

Figure 7.

Maximum principal stresses for each crown design configuration (bilayered restoration;trilayered restoration with interlayer of homogeneous composition; and trilayered restoration with interlayer of graded interlayer) in alumina and zirconia based restorations.

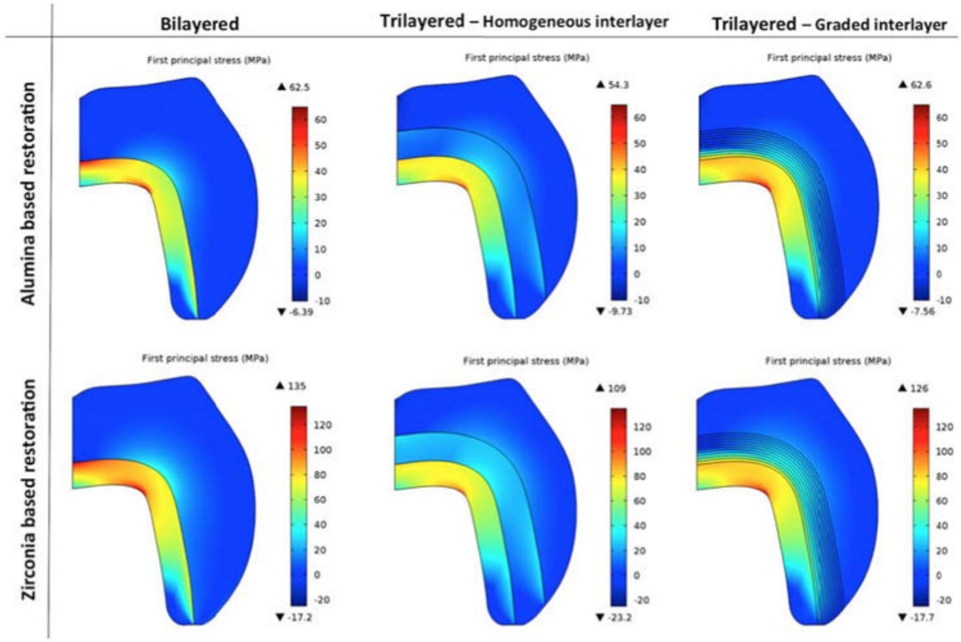

Figure 8.

Stress maps showing the maximum principal stresses for the different crowns' constructive designs: (a) Bilayered: sharp transition between framework and veneer; (b) Trilayered: interlayer of constant composition (porcelain volume fractions of 30%) between framework and veneer; and (c) Trilayered: compositionally stepwise graded interlayer between framework and veneer. Interlayer thickness was 0.75mm.

Table 1

Temperature-dependent properties of dental porcelains

Elastic modulus (GPa)				70
Poisson's ratio				0.26
Density (kg/m^3)				2431
Temperature (°C)	Conductivity (W/m°C)	Specific heat (J/kg°C)	$CTE^{alumina}$ (10^{-6}/°C)	$CTE^{zirconia}$ (10^{-6}/°C)
25	1.37	734	6.48	9.05
100	1.35	841	6.65	9.15
200	1.32	947	6.78	9.29
300	1.28	1021	6.85	9.4
400	1.23	1071	6.94	9.52
500	1.19	1106	7.13	9.65
550	1.14	1120	7.23	9.77

Table 2

Temperature-dependent properties of zirconia

Temperature (°C)	Conductivity (W/m°C)	Specific heat (J/kg°C)	Density (kg/m^3)	Elastic modulus (GPa)	CTE (10^{-6}/°C)
25	2.92	466	6095	210	10.17
100	2.88	513	6080	208.7	10.42
200	2.83	546	6060	205.4	10.62
300	2.78	568	6040	200.7	10.87
400	2.73	584	6019	194.6	11.10
500	2.68	597	5999	187.4	11.31
550	2.66	603	5989	183.3	11.52

Table 3

Temperature-dependent properties of alumina

Temperature (°C)	Conductivity (W/m°C)	Specific heat (J/kg°C)	Density (kg/m^3)	Elastic modulus (GPa)	CTE (10^{-6}/°C)
25	32.82	781	3998	399.9	6.96
100	25.37	937	3991	395.8	7.23
200	19.64	1026	3982	390.3	7.71
300	16.12	1082	3972	384.8	8.08
400	13.72	1124	3962	379.3	8.38
500	11.98	1157	3953	373.8	8.75
550	11.27	1172	3947	371.0	8.91

Table 4

Maximum principal stress in a bilayered restoration at the interface between framework and veneer (F/V) and at the inner part of the framework (F).

Location	Type of Restoration	
	Alumina/porcelain	Zirconia/porcelain
F/V interface	63 MPa	122 MPa
Framework (F)	60 MPa	135 MPa

Table 5

Flexural strength and Weibull modulus of alumina, zirconia and feldspar-based porcelain (4-point bending test) [42]

	Flexural strength [MPa]	Weibull modulus, m
Alumina	364	9.6
3Y-TZP zirconia	1118	10.8
Feldspar-based porcelain	112	18