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Effects of different ceramic and composite materials on stress distribution in inlay and onlay cavities: 3-D finite element analysis

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To reduce loss of tooth tissue and to improve esthetic results, inlay and onlay restorations are good treatment choices for extensive cavities in posterior teeth. The aim of this paper was to evaluate, by means of three-dimensional finite element analysis, the effects of restorative material and cavity design on stress distribution in the tooth structures and restorative materials. Two different nanofilled composites and two different all-ceramic materials were used in this study. A permanent molar tooth was modeled with enamel and dentin structures. 3-D inlay and onlay cavity designs were created. Von Mises, compressive, and tensile stresses on the restorative materials, core materials, enamel, and dentin were evaluated separately. On the effect of restorative material, results showed that in the case of materials with low elastic moduli, more stress was transferred to the tooth structures. Therefore, compared to the nanofilled composites, the all-ceramic inlay and onlay materials tested transferred less stress to the tooth structures. On the effect of cavity design, the onlay design was more efficacious in protecting the tooth structures than the inlay design.

Keywords: Finite element analysis, All-ceramic, Nanofilled composite

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INTRODUCTION

For the two-fold objectives of reducing tooth tissue loss and improving esthetic results, composite resin or all-ceramic inlays and onlays may be used for the restoration of extensive cavities in posterior teeth[1-3].

Composite resins were first used as anterior restorative materials. However, in the course of time, these materials are increasingly being used in stress-bearing posterior restorations. To address the string of known problems faced by direct composite restorations — such as limited depth of cure, short functional lifetime, and poor proximal contact, indirect composite techniques for processing outside the mouth were thus developed. With indirect composite techniques, more effective polymerization can be achieved with curing ovens using heat, light or pressure alone, or in combination. Consequently, the physical properties of composite restorations are vastly improved by virtue of void-free composites that have achieved maximal polymerization. In addition, with indirect composite restorations, the occlusion and proximal contacts can be adjusted more easily and there is better placement control[4,5].

In the pursuit of better and improved dental restorative materials, nanotechnology was introduced for dental composites[6,7]. In the last five years, several manufacturers have produced nanofilled restorative materials with a filler size ranging from 5 to 100 nm. Nanofilled composite resins deliver increased esthetics, strength, and durability vis-à-vis the hybrid composite materials, and are hence more resistant to wear, attrition, and fracture[8-12]. They have low polymerization shrinkage and high flexural strength because of the high filler load of small-sized fillers. With respect to clinical significance, nanofilled resin composites can be used for the restoration of both anterior and posterior cavities with direct and indirect techniques[6,7,11,12].

Apart from nanofilled composites in restorative dentistry, ceramic is also a very successful and durable tooth-colored restorative material which has been in use for many years. With recent innovations in formulation and firing techniques, it has been possible to construct accurate inlays and onlays with dental ceramics. Notably, indirectly prepared inlay and onlay restorations have some advantages like maintaining a more stable occlusion than polymers and possessing superior color stability[4,5]. In this connection, the IPS Empress 2 system was introduced as an all-ceramic material for inlays, onlays, single-unit restorations as well as for three-unit fixed partial dentures of the anterior and premolar region. This system utilizes a lithium disilicate framework that is veneered with a fluorapatite-based veneering porcelain[13].

On the fabrication of all-ceramic restorations, rapid advances in technology have spawned several computerized devices that can fabricate ceramic inlays and onlays from high-quality ceramics in a matter of minutes. Owing to their superior fracture strength and toughness as compared to other dental ceramic systems, the use of zirconia-based ceramics for dental restorations has risen in popularity[4]. Currently, several CAD/CAM systems which use zirconia-based ceramics for frameworks are available in the market, such as the Lava CAD/CAM System (3M ESPE).

Against the backdrop of such a wide array of dental materials and restorative techniques, finite

element analysis (FEA) has been widely employed in many researches to investigate their impact and effect on stress distribution. Based on the results indicated in published literature[14-16], FEA is deemed as an effective tool to evaluate the biomechanical characteristics of these dental restorative materials and systems, whereby the results carry significant clinical implications.

For dental restorative materials, a foremost requirement is the ability to withstand the masticatory forces in the oral cavity. In this connection, the elastic modulus is an important property as it plays a pivotal role in the longevity of the dental restoration and the soundness of the surrounding dental tissue. Ideally, the elastic properties of restorative materials should be close to those of the tooth structure to yield a more uniform stress distribution. However, the tooth consists of enamel and dentin that are very different elastically. If both were to be replaced, two distinct restorative materials should be used and as such, one of them should be chosen as a standard[7,17-19].

Little information is available on the stress analysis of inlays and onlays made from porcelain and composite resins. Therefore, the aim of this study was to evaluate, by means of 3D finite element analysis, the different types of stress that occurred in the composite and ceramic inlays and onlays and in the tooth structures: von Mises (VM), minimum principal stress (compressive) and maximum principal stress (tensile).

MATERIALS AND METHODS

Restorative materials

In the present study, two nanofilled resin composite restorative materials were selected for investigation: Filtek Supreme XT (3M ESPE, St. Paul, MN, USA) and Grandio (Voco, Cuxhaven, Germany). As for the all-ceramic materials, they were IPS Empress 2 (Ivoclar Vivadent, Schaan, Liechtenstein) and Lava (3M ESPE, St. Paul, MN, USA).

Inlay and onlay cavity designs

A permanent right lower first molar tooth was modeled with enamel and dentin structures. 3-D inlay and

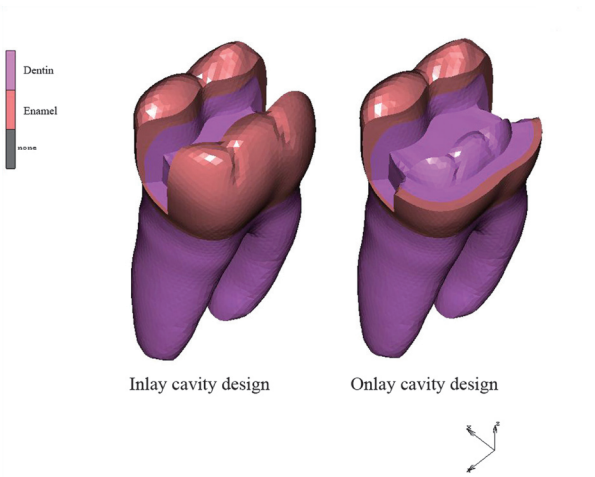


Fig. 1 Inlay and onlay cavity designs.

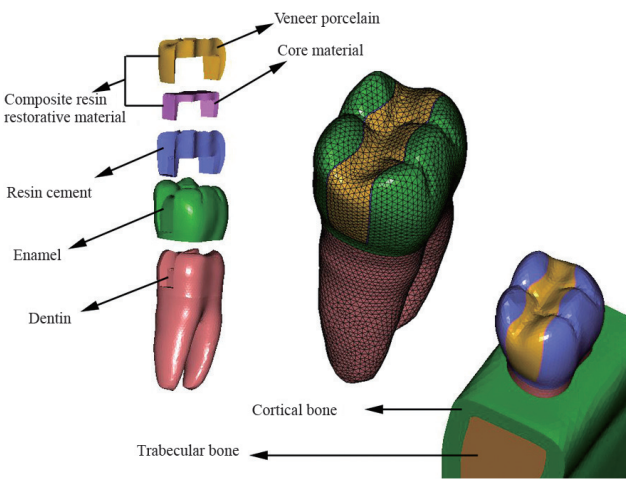


Fig. 2 FEA model used in the study.

Table 1 Elastic moduli, Poisson's ratios, and references of the materials used

	Elastic moduli (GPa)	Poisson ratios (v)	References
Enamel	72.7	0.33	3
Dentin	18.6	0.31	3
Variolink II	8.3	0.35	3
Grandio	20.4	0.33	8
Filtek Supreme	12.7	0.35	8
IPS Empress 2 Core	102	0.3	17
IPS Empress 2 Veneer	67.2	0.3	17
Lava Core	210	0.23	18
Lava Veneer	80	0.265	18
Cortical bone	13.7	0.30	10
Spongious bone	1.37	0.30	10

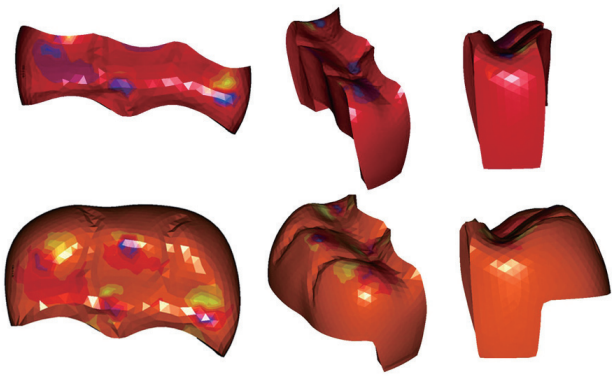


Fig. 3 Inlay and onlay restoration designs.

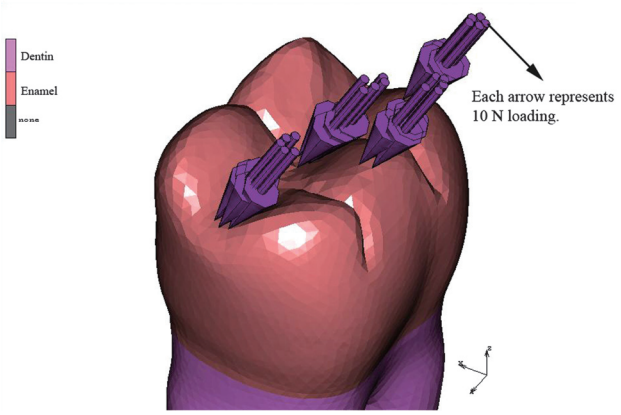


Fig. 4 Nodes selected for loading.

onlay cavity designs were created with 2.7 mm cavity depth, 2.3 mm isthmus width, and 1.2 mm gingival wall width. The prepared cavity walls tapered with 5° from the cavity base to the cavosurface. In the onlay cavity, functional cusps were reduced and included in the cavity (Fig. 1).

Surrounding bone was modeled as cortical and trabecular bone, which were assumed to be isotropic, homogeneous, and linearly elastic. As mandibular cortical bone was considered to be homogeneous type II bone, a new mesh structure was constructed for the cortical bone of 1.5 mm thickness. The model was fixed from the medial and lateral surfaces of the mandible. A resin cement (Variolink II, Ivoclar Vivadent, Schaan, Liechtenstein) of 0.1 mm thickness was then created to cover the entire cavity surface, as shown in Fig. 2. The elastic moduli and Poisson's ratios of the materials used are shown in Table 1.

For the all-ceramic restorative materials, a minimal core thickness of 0.8 mm was modeled. As for the rest of the restorative material volume seen in Fig. 3, it was described as porcelain veneer.

The mesh structure of the solid 3D model was created using the Mark Mentat FEA program (MSC Software, Santa Ana, CA, USA). To generate the solid model, tetrahedral solid elements were prepared whereby 110,231 elements and 21,231 nodes (intact tooth) were used in the current study. An oblique loading of 200 N was applied to the central fossa, distal marginal ridge, mesiobuccal cusp tip, and distobuccal cusp tip. At each selected loading point, an oblique loading of 50 N was applied to five nodes (10 N for a node), as illustrated in Fig. 4.

For both the inlay and onlay cavity designs, 3-D finite element analysis was used to evaluate the VM, compressive, and tensile stresses on the restorative materials, core materials, enamel, and dentin.

RESULTS

To analyze stress distribution and location, all the created structures were isolated from the rest of the model. For both cavity designs, the VM, compressive, and tensile stresses on the restorative materials, core materials, enamel, and dentin were evaluated separately.

Stress distributions in enamel

For VM stress, the highest stress value was exhibited by Filtek Supreme XT inlay restoration at 117.76 MPa (Fig. 5). It was also observed that VM stresses were higher in inlays than in onlays.

For tensile stress, the highest value was exhibited by Filtek Supreme XT inlay restoration at 67.86 MPa, followed by Grandio inlay restoration at 50.48 MPa. Then, comparing across the entire spectrum of restorative materials and inlay-*versus*-onlay cavity designs, the tensile stress values were close to one another but lower than that in the intact tooth (Fig. 5).

For compressive stress, the decreasing order of magnitude as seen in Fig. 5 is as follows: Intact tooth> Inlay cavity> Onlay cavity. In terms of stress location, compressive stress occurred in the distobuccal cusp tip and in the lingual cervical region neighboring the cortical bone (Fig. 6).

Stress distribution in dentin

For VM stress, the highest value was exhibited by Filtek Supreme XT inlay restoration at 39.64 MPa (Fig. 7) and it occurred in the lingual cervical region neighboring the cortical bone. It was also observed that VM stresses were higher in inlays than in onlays.

For tensile stress, the highest value was also exhibited by Filtek Supreme XT inlay restoration at 26.32 MPa (Fig. 7) and it occurred in the buccal cervical region neighboring the cortical bone. When comparing across the entire spectrum of restorative materials and

inlay-*versus*-onlay cavity designs, the tensile stress values were close to one another: between the inlay and onlay cavity designs, and among the four tested restorative materials within each cavity design.

For compressive stress, the highest value was exhibited by Filtek Supreme XT inlay restoration at 46.53 MPa (Fig. 7) and it occurred in the lingual cervical region neighboring the cortical bone. It was also observed that compressive stresses were higher in inlays than in onlays. For the onlay restorations, similar compressive stress values were obtained among the different restorative materials. On the overall, the decreasing order of compressive stress magnitude for both inlay and onlay cavity designs is as follows: Filtek Supreme XT > Grandio > IPS Empress 2 > Lava.

In terms of stress location for tensile stress, the latter occurred in the lingual part of the cavity base and in all the walls of the proximal box when the inlay and onlay cavities were restored with composite resins (Fig. 8). As for all-ceramic inlay and onlay restorations,

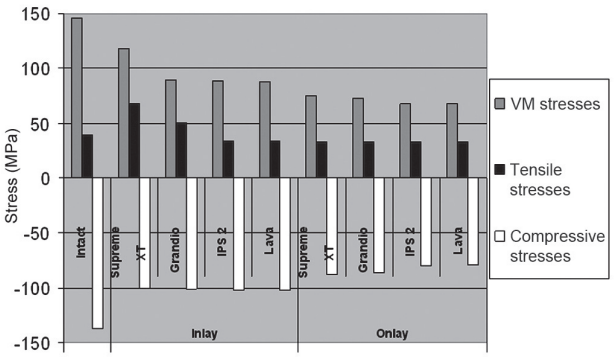


Fig. 5 Compressive, tensile, and von Misses stresses which occurred in enamel.

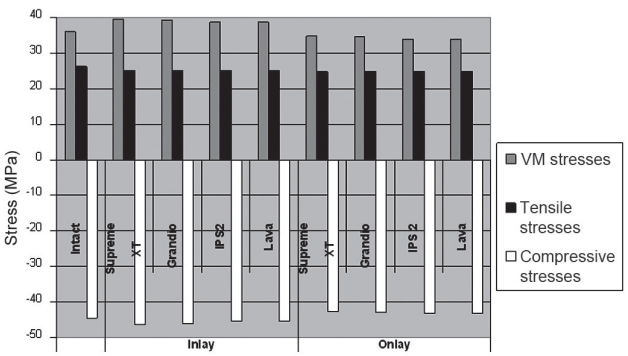


Fig. 7 Compressive, tensile, and von Misses stresses which occurred in dentin.

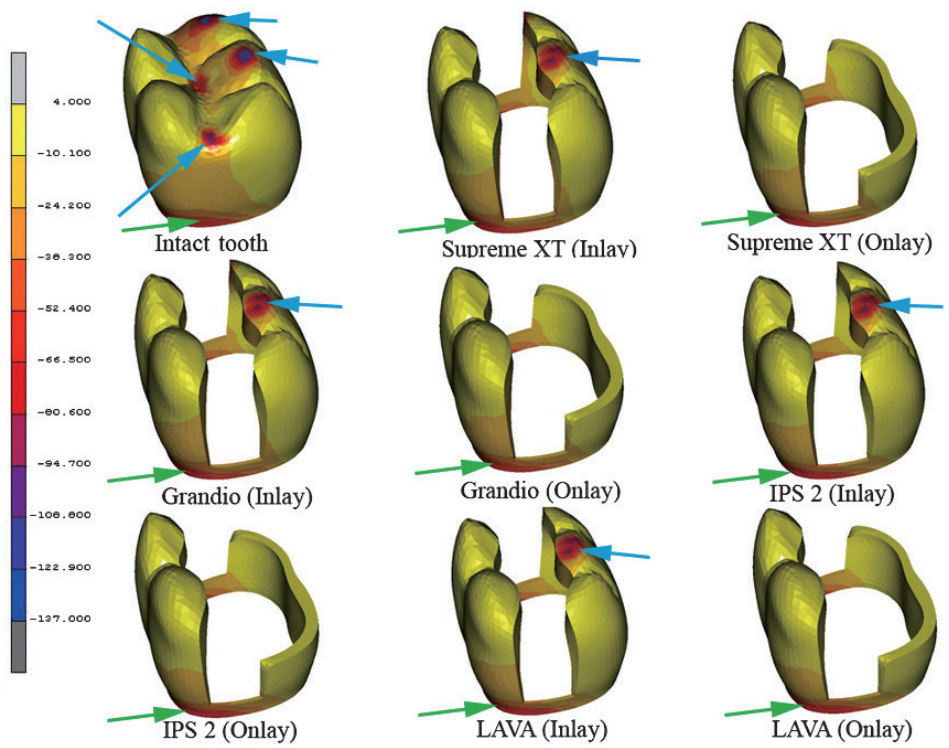


Fig. 6 Compressive stress which occurred in enamel in intact tooth, and with inlay and onlay cavities. Blue arrows show the high compressive stress patterns at loading points. Green arrows show the secondary compressive stress patterns near the cervical region.

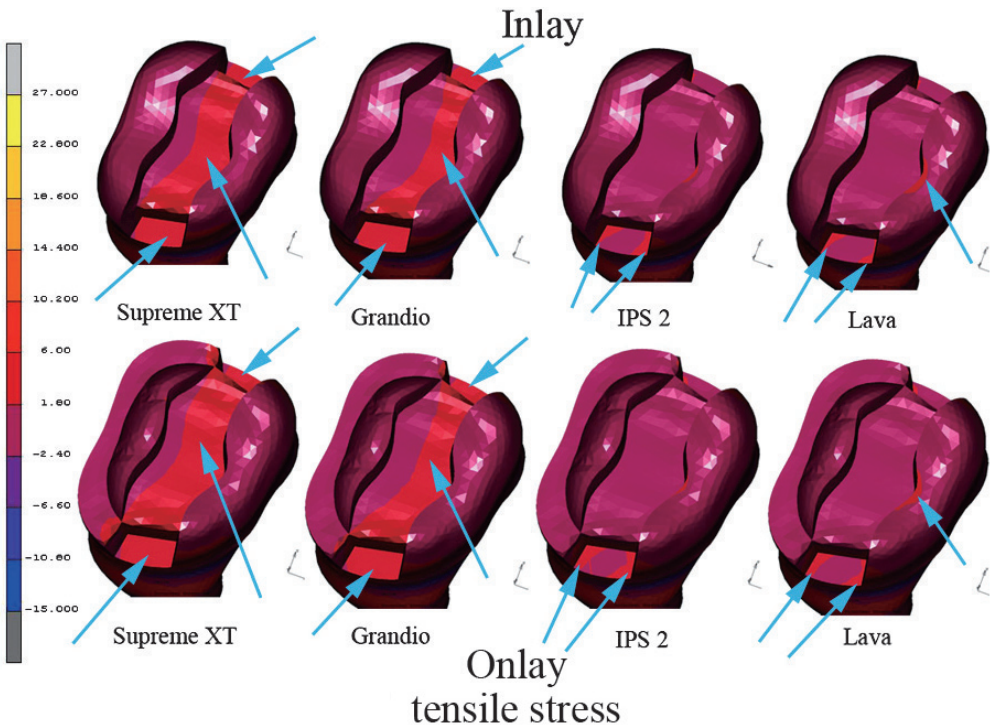


Fig. 8 Tensile stress which occurred in dentin with inlay and onlay cavity designs. Blue arrows show the tensile stress patterns on cavity base and proximal box base for composite restorative materials. For all-ceramic restorative materials, stress patterns were observed in the proximal box corners.

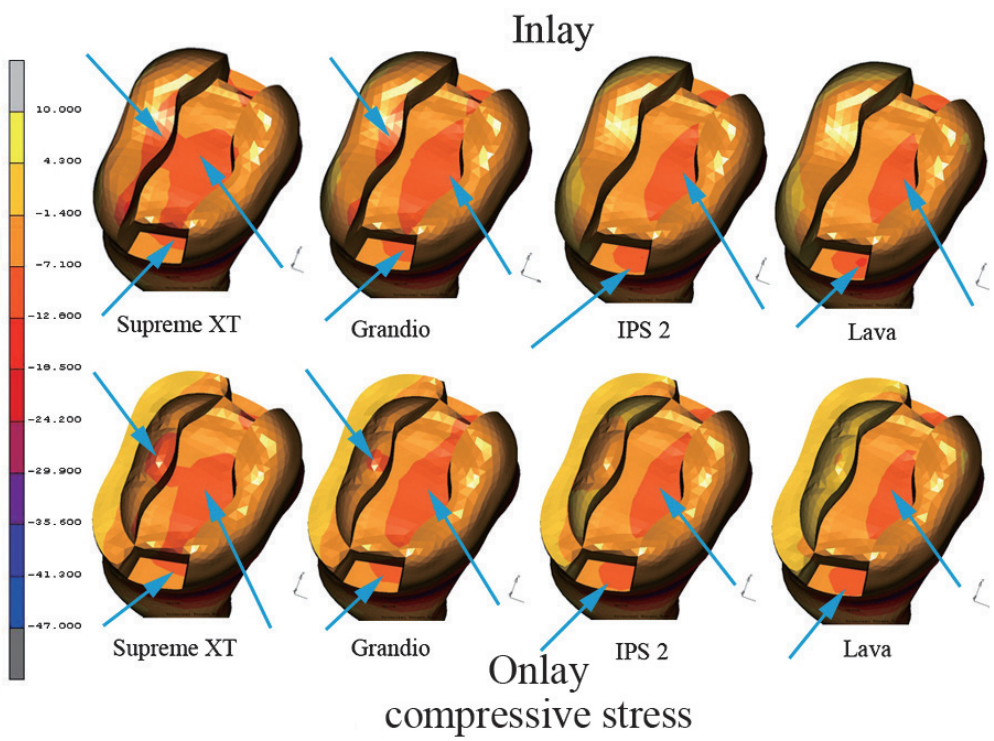


Fig. 9 Compressive stress which occurred in dentin with inlay and onlay cavity designs. Blue arrows show the compressive stress patterns on cavity base, proximal box base, and aligned distobuccal cusp for composite restorative materials. For all-ceramic restorative materials, stress patterns were observed in the cavity base and proximal box base.

tensile stress did not occur in the cavity base but at the corners (angles) of the proximal box.

In terms of stress location for compressive stress, the latter occurred in the inner surface of the buccal wall (aligned with the mesiobuccal and distobuccal cusps) and in the lingual part of the cavity base when the inlay and onlay cavities were restored with composite resins (Fig. 9). Compressive stress was distributed over a wide area in the cavity base but over a narrow area in the gingival wall of the cavities. On the contrary, for all-ceramic inlay and onlay restorations, compressive stress was distributed over a narrow area in the cavity base but over a wide area in the gingival wall of the cavities.

Stress distribution in core material

As shown in Fig. 10, higher VM, tensile, and compressive stresses occurred in the Lava core material than in IPS Empress 2 core material. Moreover, higher VM and compressive stresses occurred in the onlay design than

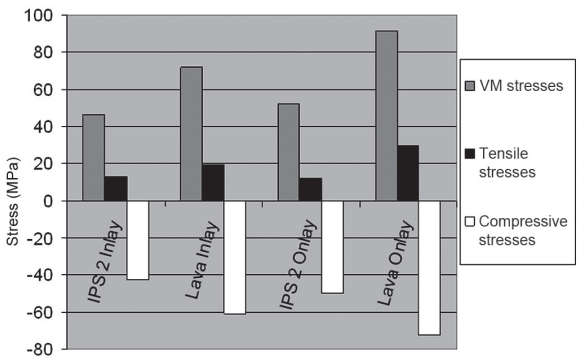


Fig. 10 Compressive, tensile, and von Misses stresses which occurred in the core materials.

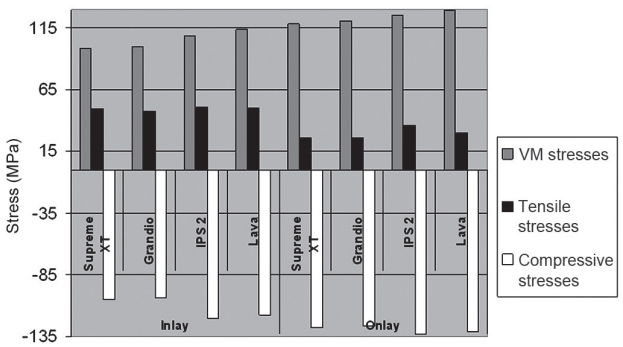


Fig. 13 Compressive, tensile, and von Misses stresses which occurred in the restorative materials.

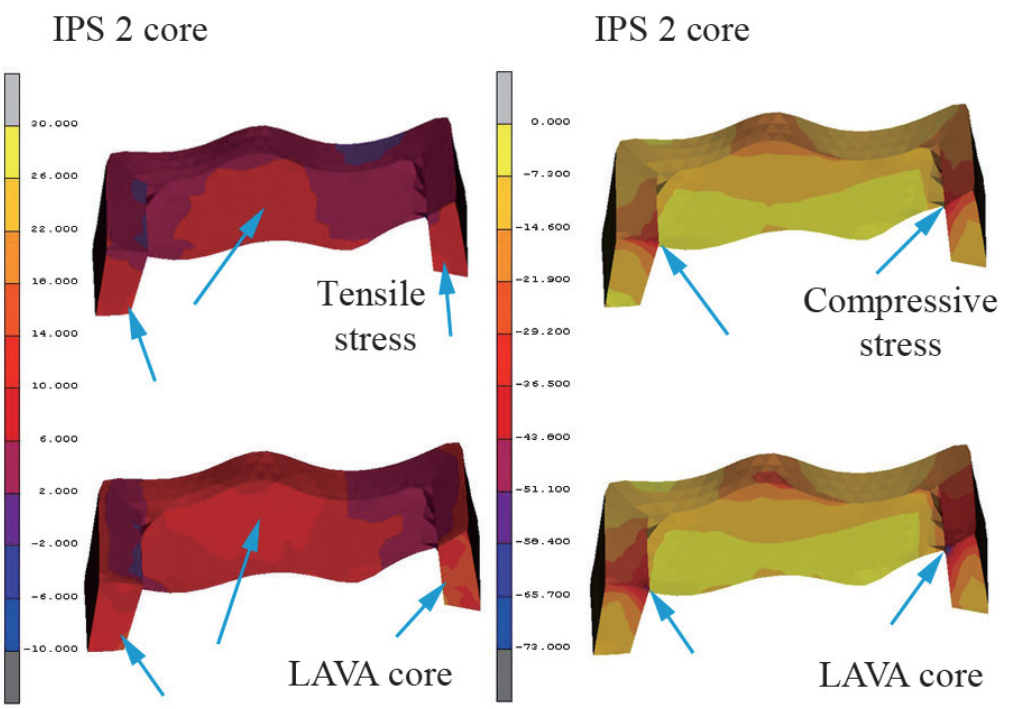


Fig. 11 Compressive and tensile stresses which occurred in inlay cores. Blue arrows show the high compressive and tensile stress patterns on the inner corners of the adjacent proximal box for. In addition, secondary tensile stress patterns were observed in the adjacent cavity base for both Lava and IPS Empress 2 core materials.

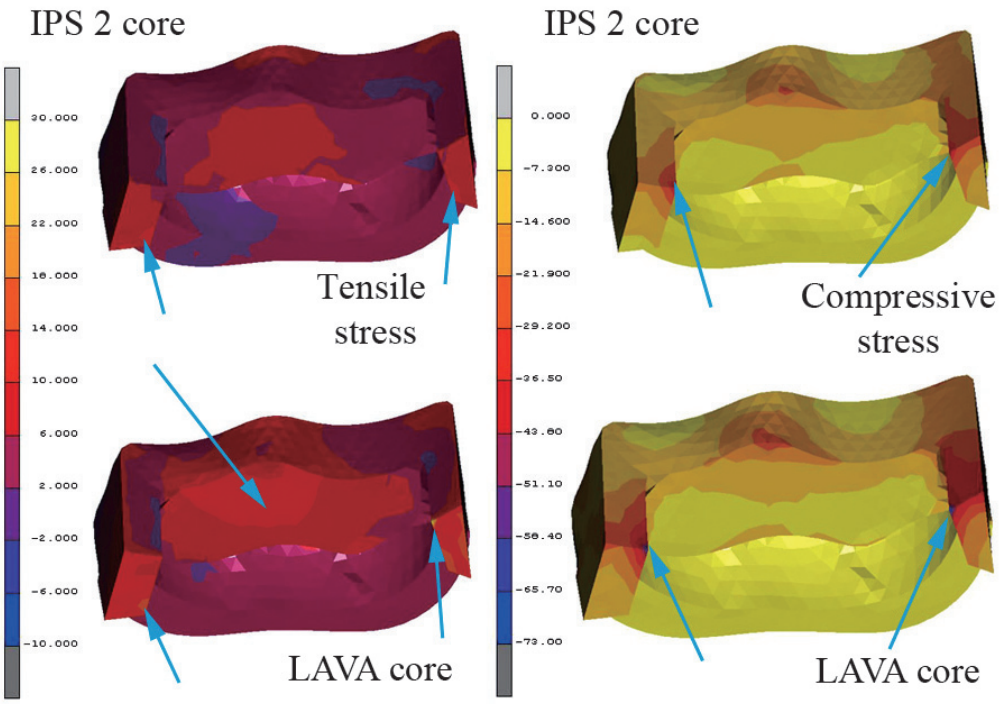


Fig. 12 Compressive and tensile stresses which occurred in onlay cores. Blue arrows show the high compressive and tensile stress patterns on the inner corners of the adjacent proximal box for. In addition, secondary tensile stress patterns were observed in the adjacent cavity base for Lava core material.

in the inlay design. For VM stress, the highest value was observed in the onlay cavity with Lava core material at 91.6 MPa.

In terms of stress location for the inlay design, high compressive and tensile stress patterns were observed in the inner corners of the adjacent proximal box (Fig. 11). In addition, secondary tensile stress patterns were produced in the adjacent cavity base in both IPS Empress 2 and Lava core materials.

In terms of stress location for the onlay design, high compressive and tensile stress patterns were observed in the inner corners of the adjacent proximal box (Fig. 12). In addition, secondary tensile stress patterns were produced in the adjacent cavity base in the Lava core material.

Stress distribution in restorative materials

With the restorative materials, higher VM, tensile, and compressive stresses occurred in the all-ceramic veneering materials than in the composite resin restorative materials (Fig. 13). For VM stress, higher values were exhibited by the onlays than the inlays. And for both cavity designs, the decreasing order of VM stress intensity is as follows: Lava > IPS Empress 2 > Grandio > Supreme XT.

DISCUSSION

In present-day dentistry, inlay and onlay restorations have become the frequently-resorted-to treatment options to make the residual tooth structure strong and resilient. Inlays restore central cavities in teeth, whereas onlays restore one or more cusps and may completely cover the occlusal surface. To restore the inlay and onlay cavities of posterior teeth, gold, composite resins, and dental ceramics are the typically used dental materials.

To date, confusing and contradicting results have been obtained from studies that investigated the effects of cavity design and restorative material on stress distribution in tooth structures[20,21]. With a view for a better understanding of this issue, a 3D finite element analysis of stresses associated with the inlay and onlay designs of all-ceramic and composite resin restorations in molars was performed in this study.

Teeth in the posterior region are subject to functional and para-functional forces of varying magnitudes and directions[22]. Intraoral loads vary widely and have been reported to range from 10 to 431 N[4]. Nonetheless, all the studies clearly showed that oblique loads generate more stress than loads directed along the long axis of the tooth[23-25]. In the current study, an oblique loading of 200 N was applied to the central fossa, distal marginal ridge, mesiobuccal cusp

tip, and distobuccal cusp tip. The force corresponded to the force acting on the mandibular molar during the closing phase of mastication[26]. Functional cusps of the mandibular molar as well as the in-contact functional cusps of the opposite molar were selected as the loading nodes.

Apart from functional loading, the restorative procedure has been identified to influence stress and strain produced in restored teeth. A number of studies that analyzed the biophysical stress and strain in restored teeth have shown that restorative procedures can make the tooth crown more deformable, and teeth could be strengthened by increasing their resistance to crown deformation[27-29].

Some investigators have reported that teeth with inlays appeared more resistant to fractures than those with onlays[30]. However, there were also reports about a higher number of failures in inlay restorations clinically[31]. In the present study, comparison of the VM stresses in dentin showed that higher values were observed for the inlay cavity design than for the onlay cavity design. Further, VM stresses in the intact tooth were higher than those with onlays but lower than those with inlays.

Regarding the stresses that occurred in enamel, it was revealed that VM and compressive stresses were lower with the onlay design than with the inlay design. Stappert *et al.*[30] investigated the effects of different cavity preparation designs on fracture resistance and reported that teeth with inlays were more resistant to fractures than those with onlays. In the current study, the inlay cavity design caused higher stress values in tooth structures than the onlay cavity design. It should be pointed out that in the study by Stappert *et al.*[30], the specimens were subjected to dynamic loading (49 N) and the load was applied directly on the centre of restorations at an angle of 180° to the long axis of the tooth. In the present study, 200-N oblique loading was applied on four different nodes. As restorative materials do not cover functional cusps in the inlay cavity design, forces were applied directly on the tooth structures. On the contrary, as the composite resin or ceramic material covers the functional cusps in the onlay cavity design, forces were partially absorbed by the restorative material and partially transferred to the cavity walls. These differences in experimental strategy might be the reasons for conflicting results between the present study and that of Stappert *et al.*[30].

Regarding the stresses that occurred in the restorative materials, it was revealed that VM and compressive stresses were higher for the onlay cavity design. With the onlay design, all loading points were located on the restorative material and this could have thus caused the higher stress values. On the contrary, tensile stress was approximately two times higher for the inlay cavity design than for the onlay cavity design.

To date, various studies have been undertaken to compare the effects and results of different restorative materials being used to restore inlay and onlay cavities. According to some authors, ceramic inlays maintain better anatomic form of the surface as well as stabilize the weakened cusps better than composite resin inlays[29,32,33]. On the other hand, other authors reported that teeth restored with composite resin inlays exhibited higher strength than those restored with ceramic inlays[34,35]. Still, there were reports which showed that the fracture resistance of teeth with both ceramic and composite resin inlays was similar[36,37].

Composite resins are characterized by mechanical properties similar to dentin. Their elastic modulus, ultimate compressive strength, and hardness depend on the volume of filler in the restorative material. Highly-filled nanofill composites have better physical properties than hybrid composites, by virtue of the high filler load of the nanofill composites because of the small size of the filler particles. When used for indirect and direct restorations, composite resins exhibit similar flexural strength, flexural modulus, and hardness. For the composite resins used in the current study, Grandio contained 71.4% filler by volume while Filtek Supreme XT contained 57.7%, and their elastic moduli were 20.4 and 12.7 respectively[4,11,12,38,39]. With regard to the compressive stress produced in dentin, the highest value was exhibited with an inlay cavity restored by Filtek Supreme XT composite resin (46.53 MPa). Among all the tested restorative materials, the magnitude of compressive stress in dentin in a decreasing order was Filtek Supreme XT > Grandio > IPS Empress 2 > Lava. The low elastic modulus values of the composite resins accounted for this result. Whereas a large amount of compressive stress was transferred to the tooth structure with Filtek Supreme XT and Grandio, stresses were partially absorbed and partially transferred to the cavity walls when ceramic materials were used.

As for Lava and IPS Empress 2 all-ceramic systems, they possess good physical properties which can be utilized to create inlays, onlays, crowns, and bridges[40]. The elastic modulus values of these ceramic veneer materials are close to enamel and support enamel better than resin composites. As a result, VM and compressive stresses that occurred in enamel were lower when cavities were restored with Lava and IPS Empress 2.

In a 3-D finite element analysis study by Ausiello *et al.*[22] on stress distribution in inlays restored with resin composites and ceramic, they reported that Class II MOD restorations using glass-ceramic inlay materials created higher stress levels at the cusp and the internal sides. Similarly, Pest *et al.*[41] stated that restorative materials which were more rigid were more stress-resistant, but transferred a large part of the functional stress to the less rigid substrate (dentin) and hence elevated the risk of root fractures. In contrast to these findings, Mesquita *et al.*[18] reported that if a composite had a low elastic modulus, it would deform more under functional stress. Consequently, it might become possible that the tooth structure would suffer from a catastrophic fracture or that the bond between tooth and restoration would be compromised, thus

leading to marginal gap deformation, postoperative sensitivity and secondary caries. In the present study, it was found that ceramic inlays and onlays created lower stress levels in the tooth structures than composite resin inlay and onlays — and these findings were compatible with the results of Mesquita *et al.*[18]. This was because the elastic modulus values of the composite resins were lower than enamel, which meant that they could not provide enamel with enough support. For this reason, the stresses that occurred in the tooth structures were higher than those caused by the ceramic materials.

The bonding strength between tooth substrates and restoratives is another important contributing factor to a successful restoration. Forces directed to the restorative material may cause adhesive and cohesive failures in the resin cement. Dejak and Milotkowski[3] reported that failures in resin cements might be influenced by the restorative material used.

According to published literature, the tensile bond strength (TBS) of Variolink II cement with Al_2O_3-sandblasted zirconium oxide was 16.6 MPa and that with Al_20_3-sandblasted IPS Empress 2 was 10.6 MPa[42,43]. Within the limitations of the current study (force, contact area, geometry), the tensile stress in Lava core material ranged between 22 and 26 MPa and it occurred in the inner corners of the adjacent proximal box. As for IPS Empress 2, the tensile stress in the core material ranged between 10 and 14 MPa. The values obtained were higher than the tensile strength values of the materials used. Evaluation of the contact area between resin cement and dentin showed different tensile stress patterns for inlay and onlay designs. The tensile stress that occurred in dentin ranged between 1.8 and 6 MPa (Fig. 8), which was lower than the TBS value of Variolink II to dentin at 19.11 MPa[44]. In enamel, tensile stress in the gingival wall of the proximal box ranged between 11 and 22.4 MPa, which was lower than the TBS value of Variolink II to enamel at 49.3 MPa[45]. On compressive stress, the values obtained in this study did not exceed 240 MPa, which was the compressive strength value reported by the manufacturer for Variolink II.

Dejak and Mlotkowski[3] reported that porcelain inlays reduced tension at the dentin-adhesive interface and featured better potential protection against debonding at the dentin-restoration interface, as compared to composite resin inlays. In the current study, tensile stress values obtained with both resin composite and ceramic restorative materials were close to each other; however, their stress patterns were different. For inlay cavities restored with composite resin materials, tensile stresses were observed in the lingual part of the cavity base and in all the walls of the proximal box in dentin. However, tensile stress did not occur in the cavity base when ceramic restorations were used. In the latter case, stress occurred in the corners (angles) of the proximal box. For onlay cavities, stress distributions were similar to those observed for inlay cavities (Fig. 8).

CONCLUSIONS

Within the limitations of this study, the following conclusions were drawn:

1. Materials with low elastic modulus values transferred more functional stress to the tooth structures.
2. On the effect of restorative material, the all-ceramic inlay and onlay materials tested transferred less stress to the tooth structures than the composite resins.
3. On the effect of cavity design, the onlay design protected the tooth structures more efficaciously than the inlay design.

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