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EFFECT OF MATERIAL AND OCCLUSAL THICKNESS ON STRESS DISTRIBUTION OF SINGLE CROWN RESTORATION: 3D FINITE ELEMENT ANALYSIS

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ABSTRACT

Objective: polymer-infiltrated ceramics materials and glass ceramics are commonly used nowadays in dental field. However, their thickness is considered critical especially when applied in areas subjected to heavy forces. Thus, the purpose of this study was to assess the stresses induced in mandibular first molar restored by polymer-infiltrated ceramic and glass ceramic crown with different occlusal thicknesses (1 mm and 1.5 mm). **Materials and methods:** A 3D finite element model of mandibular first molar restored with CAD/CAM lithium disilicate glass ceramic [LD; IPS e.max CAD] and polymer-infiltrated ceramic [VE; VITA Enamic] crowns with different occlusal thicknesses (1 and 1.5 mm) were constructed (Models: LD1, LD1.5, VE1, VE1.5). A static axial load (200 N) was applied in all groups. Using sophisticated finite element analysis software, von Mises stresses were assessed. **Results**: The highest stress values in the restorations were in model VE1.5 followed by LD1, then LD1.5, and the least was VE1. LD caused more stresses in the underlying cement and periodontal ligament. However, crowns with 1.5mm occlusal thickness caused less stresses in the underlying cement, periodontal ligament and cancellous bone. **Conclusions**: The nature of the restorative material and the occlusal thickness affect stress distribution in teeth restored with full coverage crown

KEYWORDS: crown, ceramic, finite element analysis (FEA), hybrid, molar.

INTRODUCTION

Maximum preservation of healthy tooth structure became the new principle in teeth reduction[1] to ensure its longevity[2]. Excessive unnecessary removal of sound tooth structure may jeopardize the tooth resistance to fracture, cause pupal damage and adversely affect the restoration retention and resistance[3].

Full coverage crowns are commonly used in dentistry due to their excellent durability and retention [4]. They are used to restore teeth suffering from fractures with significant tooth loss, extensive caries or discoloration, cracks, malalignments in addition to their ability to enhance teeth shape[3]. However, they are susceptible to mechanical failure and might cause catastrophic tooth fractures[4]. Hence, trials were made to attain conservative crowns to overcome these problems. This concept became feasible by the advances in CAD/CAM restorative materials and resin cements[5].

Conventional dental ceramics offered high biocompatibility, abrasion resistance, high esthetics and color stability with adequate durability; however, they suffered from inherent brittleness and Were related to opposing teeth wear [6,7]. Composite

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resins offered easy cutting and adjustments, easy repair, high bond strength to resin-based materials and were less abrasive than ceramics [2,7]; however, their flexural strength, hardness, color stability and elastic modulus were also lower than ceramics [7].

New hybrid CAD/CAM materials were introduced to combine the advantages of both ceramics and resins[7]. VITA Enamic (VE); a polymer-infiltrated ceramic-network (PICN) material, is composed of two continuous interpenetrating ceramic and polymer networks [2]. It offered easy machining and polishing, in addition they do not require post-machining sintering or crystallization, which might adversely affect the dimensional accuracy of the final restoration [6]. They also satisfied the biomimetic concept with modulus of elasticity, hardness, flexural strength and strain at failure close to that of the natural teeth allowing better stress distribution and more resistance to occlusal forces [2,6].

However, Lithium disilicate (LD) such as IPS e.max CAD; a synthetic glass ceramic, is still commonly used in wide range of fixed prosthodontics; such as single crowns, inlays, onlays, thin veneers, three-unit fixed prostheses, and implant-supported crowns[8] because they offer excellent esthetics, color stability, bondability and mechanical properties[2,3].

The nature and mechanical properties of restorative materials plays an important role in success and survival rate[3,4]. Thus, it is imperative to understand how stresses from masticatory forces are distributed in different materials [5] especially when different restoration designs are employed.

Numerical simulations using three-dimensional finite element analysis (FEA) became widely used in dental researches, where it helps evaluate and anticipate the mechanical behavior of different structures without specimens destruction[8] at relatively low cost and standardized parameters[1]. It allows the analysis of the distribution of stresses generated by occlusal loading[4,9] in complex dental structures and helps understand the influence of different restorative materials and designs on the tooth tissues [2,4].

To date, there is limited number of studies evaluating the relation between all-ceramic crown thickness and generated stress. Thus, this study aimed to evaluate the stress distribution in mandibular molar restored with single crown restoration made of two different materials (LD and VE) with different occlusal thicknesses (1 and 1.5 mm). The null hypothesis was that the restorative material and occlusal thickness would have no effect on the stress values or distribution in mandibular first molar restored with single crown.

MATERIALS AND METHODS

A Three-dimensional (3D) digital model of mandibular first molar was generated using a digital software (SolidWorks 2014; Dassault Systèmes SolidWorks Corp) guided by the parameters specified by Hargreaves et al., 2011[10]; Mahoney, 2010 [11]; and Nelson et al., 2010[12]. The designed model comprised virtual pulp, periodontal ligament, cortical and cancellous bone in an attempt to simulate the clinical condition[2,13]. Periodontal ligament was modeled at thickness of 0.2 mm[2], to surround all roots starting 0.5 mm apical to the cemento-enamel junction (CEJ). Consequently, the bone was modeled based on the designed periodontal ligament geometry[2].

The previously designed model was duplicated; rendering two main models; each was assigned to one of the two tested occlusal crown thicknesses (1 and 1.5mm). Virtual preparations and their corresponding full coverage crowns were then designed. Both prepared designs comprised 1mm deep chamfer finish line (FL) situated 0.5mm coronal to the CEJ, an axial convergence of 5 degrees and rounded angles. Crowns were designed with an external morphology corresponding to natural teeth[2]. A cement layer of 0.8mm was designed to allow analysis of areas of high stresses prone to debonding [13]. Each model was further duplicated to accommodate for the materials tested (lithium disilicate glass ceramic [LD; IPS e.max CAD] and polymer-infiltrated ceramic [VE; VITA Enamic]) rendering four models: Model LD1; LD crown with 1 mm occlusal thickness, LD1.5; LD crown with 1.5 mm occlusal thickness, VE1; VE crown with 1 mm occlusal thickness, and VE1.5; VE crown with 1.5 mm occlusal thickness.

All models' parts were assumed linear, elastic, homogenous and isotropic[4,8,13,14]. The properties of all elements constituting the model (modulus of elasticity and Poisson's ratio) are reported in (**Table 1**) based on previous literature. All contacts were ideally bonded with no interferences or gaps [5] and the external surface of the cortical bone was fixed in all directions [2].

A 200-N load[4,8,15] was vertically applied to the centric cusps and central fossa to correspond to the axial clinical load[8]. After meshing the virtual models (**Figure 1**), a linear static numerical analysis was performed using SolidWorks software (SolidWorks 2014; Dassault Systèmes SolidWorks Corp), to acquire the von Mises stress (vMS) [4,9] and its distribution throughout the tested models.

TABLE (1) Mechanical properties of structures and materials used

Structures / Elements	Modulus of elasticity (GPa)	Poisson's ratio
Prepared tooth (Dentin) [2,5]	18.6	0.3
Pulp [16]	2.1×10^{-3}	0.45
Periodontal ligament [2,6,15]	68.9×10^{-3}	0.45
Cancellous bone [2,15]	1.37	0.3
Cortical Bone [2,15]	13.7	0.3
Vita Enamic [1,2,6]	37.8	0.24
IPS e.max CAD (fully crystalized state) [1,5,8,17]	95	0.3
Resin cement [2]	8.3	0.35

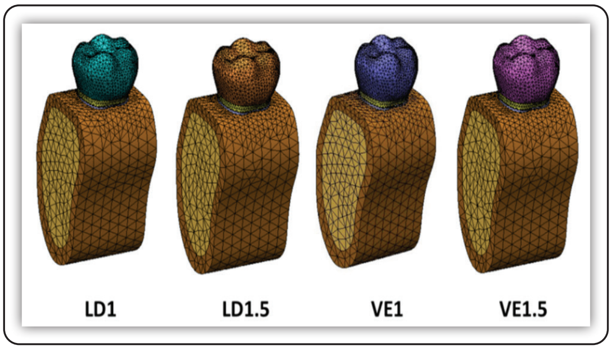

FIG (1) The meshed virtual models

RESULTS

The vMS stress distribution are presented in **Figure 2 and 3**, whereas the maximum stress values within each part of the tested models are presented in **Table 2**.

In crown restorations, stress fields were distributed on the buccal surface, buccal margin and areas of load application, however the buccal surface stresses were more pronounced in crowns with 1 mm occlusal thickness. The maximum stress location was similar in LD1.5, VE1, VE1.5 being situated at one of the load application areas (mesio-buccal cusp tip), however it was at the cervical margin in LD1. In the cement layer, stresses were seen at the buccal margins, buccal surface and at the area of load application, with the maximum stress being located at the disto-buccal margin and the buccal surface stresses being more pronounced in crowns with 1 mm occlusal thickness. In the prepared teeth, the maximum stress was found internally near the buccal pulp chamber in all models. Other stress fields were also seen at and below the buccal FL as shown in **Table 3.** The designed pulp showed stresses at the buccal pulp chamber in all models. In the periodontal ligament, stress fields were seen buccally at the cervical area both internally (tooth interface) and externally (compact bone interface), having the maximum stress situated at the most cervical edge of the tooth interface aspect. In cancellous bone, stress fields were seen at mid-cervical areas at the buccal and lingual side having the buccal stresses more pronounced (maximum stress) in all models. Finally, in the cortical bone, stresses were seen in the coronal (maximum stress) and inner side (periodontal ligament interface) of the buccal cortical bone followed by inner side of the lingual cortical bone in all models.

TABLE (2) The maximum vMS values (MPa) within each element of the tested models

Parts	**Model LD1**	**Model LD1.5**	**Model VE1**	**Model VE1.5**
Restoration (Crown)	19.84	19.81	19.12	20.42
Cement	17.78	17.51	16.02	15.67
Prepared tooth (Dentin)	25.01	25.23	28.13	28.58
Pulp	12.09	13.11	13.84	15.31
Periodontal ligament	16.22	15.88	15.39	15.33
Cancellous bone	9.156	8.976	9.155	8.997
Cortical bone	14.71	17.40	14.77	17.48

TABLE (3) The vMS values (MPa) seen within the prepared teeth

Prepared tooth areas	**Model LD1**	**Model LD1.5**	**Model VE1**	**Model VE1.5**
FL (DB area)	12.40	14.10	11.87	12.96
FL (MB area)	11.05	12.07	10.89	10.75
Cervical (DB area below FL)	19.10	19.29	16.97	18.54
Cervical (MB area below FL)	15.20	16.42	14.72	15.47

DB: Disto-buccal; MB: Mesio-buccal, FL: Finish line

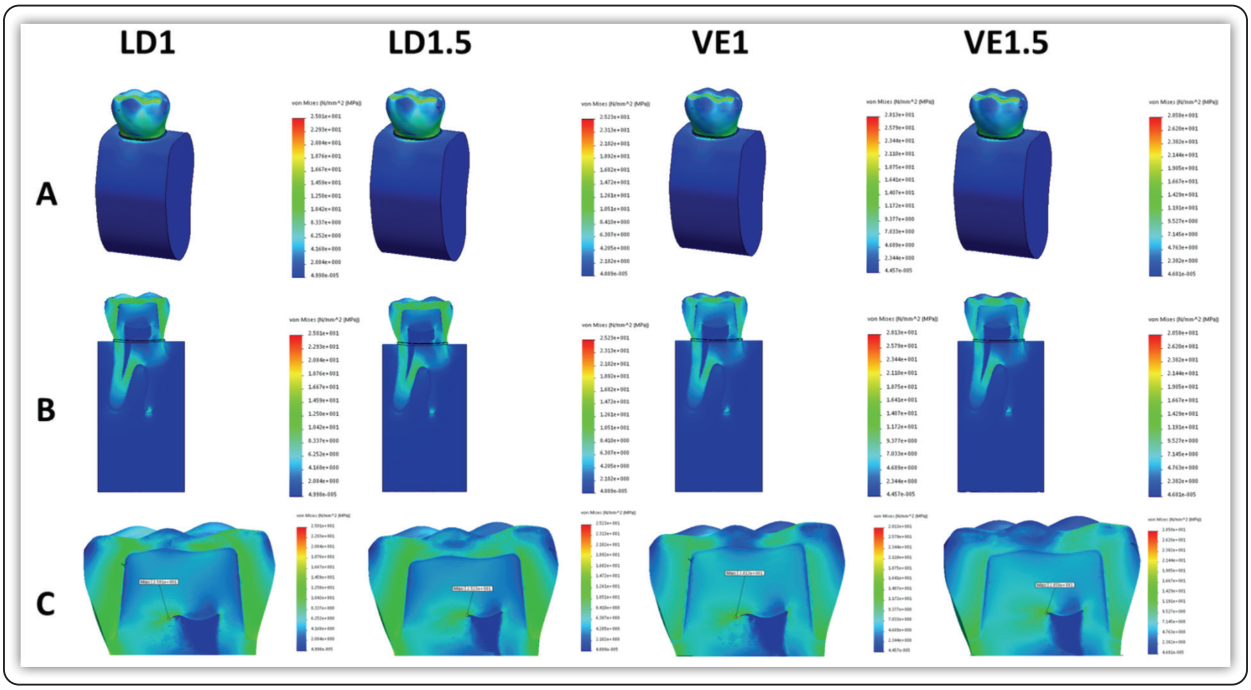

FIG (2) The resultant vMS distribution in the whole tested models; A: frontal view, B: sectioned view, C: area of highest vMS (demarcated)

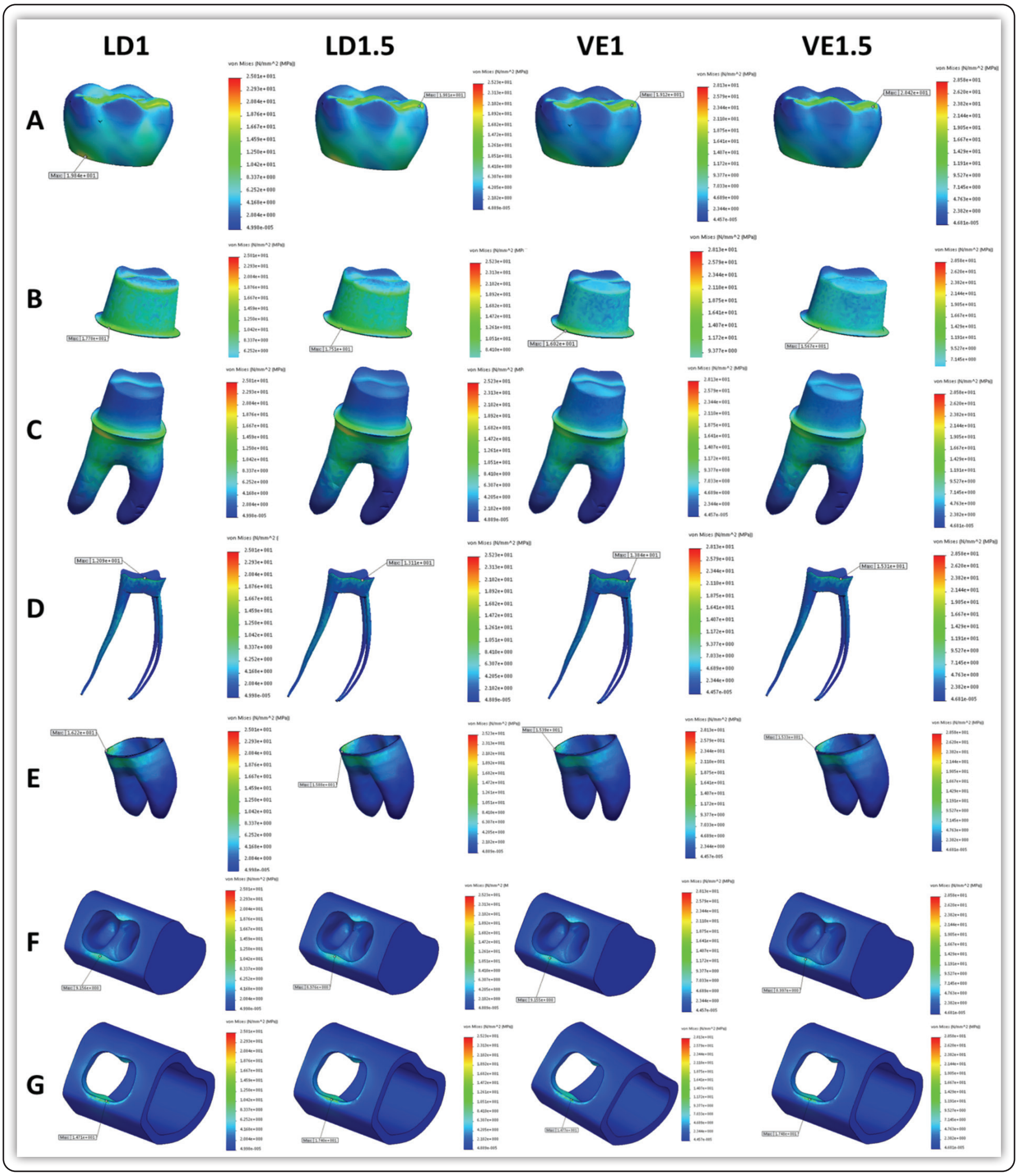

FIG (3) Stress distribution and areas of highest stress values within each part of the tested models; A: restoration B: cement layer, C: prepared tooth, D: pulp, E: periodontal ligament, F: cancellous bone, G: cortical bone

DISCUSSION

The null hypothesis of the present study was rejected, because the stress values and distribution varied among the tested groups.

Hybrid polymer-infiltrated ceramics (VE) have gained popularity in dentistry due to possessing mechanical properties close to that of the tooth structure allowing decreased elastic modulus mismatch with dentin[8]. On the other hand, LD, a brittle glass ceramic material, which possessed different physical properties from the dentin [8], still represents a reliable restorative option. Thus, the present study aimed to test the effect of different occlusal thicknesses of these two materials on the stress distribution using FEA.

3D FEA can help show stress distribution in inaccessible areas within the complex geometry of restored teeth [2]. Hence, it can help understand the biomechanical behavior of different restorative materials and designs aiding in clinical performance prediction and allowing future enhancements that can optimize dental restorations [2,6,8].

The models tested were designed based on evidence based data regarding the tooth components external and internal dimensions to ensure an accurate, realistic and reliable simulation closely relevant to the clinical condition[2]. Periodontal ligament was designed to simulate its well-known role in forces transfer[2]. Neglecting this part might cause model oversimplification with subsequent inaccurate stress distribution [2,13]. However, enamel was neglected in the present design because teeth restored with full coverage all-ceramic crowns might not have much remaining enamel after preparation[18].

The external surface of the cortical bone was constrained to obtain a realistic boundary condition to allow optimum stress prediction [2]. The load applied was corresponding to the normal occlusal forces ranging from 222 to 445 N in the molar region as presented by Zheng et al. (2021) [6].

The results of the present study emphasized the effect of occlusal thickness, material nature and modulus of elasticity on stress values and distribution.

Regarding the effect of material: In 1 mm and 1.5 mm crowns, the material with high elastic modulus (LD) caused more load transmission to the underlying cement and periodontal ligament than the material with lower elastic modulus (VE). This might indicate that stiffer crown (LD) can transfer higher loads to the underlying structures, causing greater stresses [14]. These results were consistent with Maghami et al., 2018 [14], who found higher maximum principal stresses in the underlying cement when LD crowns were tested compared to VE. The results also agreed with Homaei et al., 2018[18], who found that LD crowns caused more tensile stresses in the underlying cement than VE crowns, explaining this to be a result of the brittleness of LD, which made them unable to absorb energy, whereas, polymers in VE showed some ductility that enabled the absorption of more energy from the advancing cracks.

However, the effect of material on stress values and distribution in compact and cancellous bone was very close, which indicated that the tested material nature did not affect the stress generated in the surrounding bone.

All models showed the maximum stresses internally within the prepared teeth near the buccal pulp chamber, which can be considered a logical response to the location and direction of the forces applied. However, stresses seen at and below the buccal finish line were higher in LD models than in VE models. These findings together with those seen in the cement drew the attention to the higher risk of failure at the restoration-cement interface.

Regarding the effect of occlusal thickness: Crowns with high occlusal thickness (1.5mm) caused less load transmission to the underlying cement, periodontal ligament, and cancellous bone in both materials. In addition, the stress distribution in the cement layer was less spread on the buccal surface than in 1 mm crowns. This indicated that increasing the restoration thickness can help reduce risk of restoration debonding and periodontal affection.

However, 1.5 mm crowns transferred more stresses to the underlying tooth structure. This finding can explain the advantages of tooth conservation and its effect on tooth survival. This results coincided with the FEA study conducted by Maghami et al., 2018(14), who found that teeth with larger abutment and thinner ceramic thickness can withstand more tensile stress.

Within the restoration itself, LD1 crown exhibited more stresses than LD1.5, whereas, VE1.5 exhibited more stresses than VE1. This might be attributed to the difference in material mature as previously explained. Also, the increased stress concentration seen in cortical bone raised an important concern regarding future bone resorption and subsequent recession in crowns with higher occlusal thickness.

The static analysis performed in the present study is considered acceptable in assessing the tooth mechanical behavior(14). However, it could not simulate the cyclic fatigue loads occurring during mastication. Thus, it is recommended to conduct further FEA studies testing different ceramic materials and compare them to natural teeth under oblique and cyclic loading.

CONCLUSION

- The occlusal thickness and material nature of LD and VE can affect the stresses generated in single crowns, cement, tooth structure and periodontal ligament.
- Supporting bone is more affected by the occlusal thickness of LD and VE single crowns

CLINICAL IMPLICATION

When restoring teeth with single crowns made of LD or VE, clinicians can minimize occlusal reduction to the extent accepted for the material in patients with normal or low occlusal force, provided using resin cement with high mechanical properties

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