INTRODUCTION

Ceramics are attractive materials for dental crown restorations because of advantages such as excellent esthetics, inertness, and biocompatibility. However, ceramics are brittle and tend to fail beyond a critical load or lifetime. The failure rate of posterior all-ceramic crowns is around 3% to 4% each year, despite recent significant improvements in dental ceramic strength (e.g., high-strength alumina and zirconia cores). The main clinical failure mode is development of subsurface radial cracks in the ceramic at the interface between the crown (dental ceramic) and cement. This failure is largely caused by tensile stress concentration in the dental ceramic at the interface. Therefore, efficient methods to reduce stress at this interface should be explored.

A dental multilayer is an engineering idealization of a dental crown. This method mimics the layered structure of a crown on a real tooth. Medical and dental researchers have focused on applying finite element analysis (FEA), one of the most successful engineering computational tools, to predict stress distributions in and the mechanical behaviors of restorations, dental crowns, and fixed partial dentures. The materials were assumed to be isotropic and homogeneous. Highest von Mises stress values were found in areas directly below the load application point, and stress gradually decreased in occlusal loading direction from the external surface toward the dentin. Stress levels occurring at veneer-ceramic core-cement-dentin interfaces were shown to be lower in multilayered ceramic cores than in single-layer models.

Keywords: Finite element analysis (FEA), Functionally graded material (FGM), Stress distribution, Dental ceramic core, Dental crown

MATERIALS AND METHODS

An extracted, intact, human maxillary premolar tooth was scanned by a CT scanner (Somatom®, Siemens, Erlangen, Germany) (Ethics No.: DF RD1201/1007(P), Dental Committee, Faculty of Dentistry, University of Malaya) to obtain an image (Fig. 1a). A total of 243 images of the maxillary premolar in different axis directions were taken, and these CT data were saved in DICOM format. Eight different 3D models were created for FEA, where each 3D model was meshed and its bottom boundaries constrained. A static load was applied in the oblique direction. The materials were assumed to be isotropic and homogeneous. Highest von Mises stress values were found in areas directly below the load application point, and stress gradually decreased in occlusal loading direction from the external surface toward the dentin. Stress levels occurring at veneer-ceramic core-cement-dentin interfaces were shown to be lower in multilayered ceramic cores than in single-layer models.
selected areas. Segmentation involves the separation of an object of interest from other adjacent anatomical structures in different masks, such as a tooth (Fig. 1c), and the segmentation process in this study started with the isolation of the tooth and its supporting structures. After using Mimics to create a 3D model of the external volume of the tooth and the tooth components (Fig. 1d), this model was saved as an input file (*.inp) and imported into ABAQUS/CAE software (Professional Version, Simulia, Valley St., Providence, USA).

Eight models, which focused on the ceramic core (zirconia with/without alumina), were created in this study (Table 1). Models A, B, C, and D each represented a tooth restored with veneer, one-layer core (zirconia with/without alumina), cement, and dentin (Fig. 2a). Models E, F, and G each represented a tooth restored with veneer, two-layer core, cement, and dentin (Fig. 2b). Model H represented a natural intact tooth, which was used to study the effects of stress distribution in other models under oblique loading (Fig. 2c).

To simply the creation of 3D models for FEA, some assumptions regarding the 3D geometry and material properties of each part were made. The cementum layer that covers the surface of the root was included in the dentin portion of the tooth, because of its very thin structure. As for the influence of pulp chamber in the preparation on stresses in the crown, it was deemed negligible according to Hojjatie and Anusavice. The time-dependent setting process of the luting cement was mimicked by a time-independent elastic-plastic material property. Further, these models assumed the properties of uniform cement layer thickness, which varied from 0.025 mm to 0.140 mm in each model.

The influence of periodontal ligament on stresses in the crown was also negligible. However, Rees found that the ligament and alveolar bone were important for stress distribution. Therefore, the alveolar bone and periodontal ligament were included in the models of the current study. Temperature distribution during ceramic crown processing was uniform. Defining the periodontal ligament from CT scan images proved difficult because of its thin structure and pixel size of 0.445 mm. Thus, periodontal ligament with a thickness of 0.18 mm was generated based on the isocurve of dentin in ABAQUS. The isocurves of compact and spongy bones were also exported; their thickness was 10 mm, and their extremities corresponded to the positioning of the maxillary premolar.

Proper meshing was determined based on the convergence test and mesh size of each component, which was set to 0.5 mm. Finest meshing was beneficial in improving model accuracy, because the mesh was generated in the smallest possible size.

Linear tetrahedral solid elements (C3D3) with four nodes were used for stress analysis. C3D3 was used with 0.5-mm fine meshes to obtain accurate data, because constant tetrahedral elements exhibited slow convergence. For the natural tooth, the total number of tetrahedral elements was 493,742 with 101,091 nodes. For each control model with one-layer core, it was 534,238 elements with 112,824 nodes. For each experimental model, it was 459,536 elements with
Table 1  Models of different designs and materials created in this study

<table>
<thead>
<tr>
<th>Model</th>
<th>Designs</th>
<th>Materials and percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>First layer ceramic core</td>
<td>Zirconia (100%) without Alumina</td>
</tr>
<tr>
<td>B</td>
<td>First layer ceramic core</td>
<td>Zirconia (80%) + Alumina (20%)</td>
</tr>
<tr>
<td>C</td>
<td>First layer ceramic core</td>
<td>Zirconia (60%) + Alumina (40%)</td>
</tr>
<tr>
<td>D</td>
<td>First layer ceramic core</td>
<td>Zirconia (50%) + Alumina (50%)</td>
</tr>
<tr>
<td>E</td>
<td>Two layers ceramic core</td>
<td>First layer: Zirconia (100%) without Alumina</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Second Layer: Zirconia (80%) + Alumina (20%)</td>
</tr>
<tr>
<td>F</td>
<td>Two layers ceramic core</td>
<td>First layer: Zirconia (100%) without Alumina</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Second Layer: Zirconia (60%) + Alumina (40%)</td>
</tr>
<tr>
<td>G</td>
<td>Two layers ceramic core</td>
<td>First layer: Zirconia (100%) without Alumina</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Second Layer: Zirconia (50%) + Alumina (50%)</td>
</tr>
<tr>
<td>H</td>
<td>Natural tooth</td>
<td>Enamel + dentine</td>
</tr>
</tbody>
</table>

Fig. 2  Schematic illustrations of the geometric models: (a) Restored tooth model with single-layer ceramic core; (b) Restored tooth model with multilayered ceramic core; (c) Natural tooth model with supporting structures.

97,910 nodes. These elements were used after a pilot study revealed that the error remained below 0.1% for five mesh sizes (0.3, 0.4, 0.5, 0.6 and 0.7, respectively) in all the eight models.

A static distributed load of 200 N (23) was applied on an area of 2.5 mm² at the surface of the crown, by using the surface traction option in ABAQUS, at an oblique angle of 45° to the buccal cups of the crown to simulate masticatory occlusion (Fig. 3). The bottom surface of the compact bone of all models was fixed. The natural tooth and the tooth restored with ceramic crown restoration were perfectly bonded.

The Young’s modulus (E) and Poisson’s ratio (V) used for each component in this study were assumed to be homogeneous, isotropic, and linear elastic (Table 2) (10,17,22-26). Several functionally graded dental ceramic
(FGDC) designs with varied compositions were estimated by applying the “rule of mixture” (ROM), which was inspired by the theory of composite materials, to ensure the best FGDC combination for single-layer and multilayered ceramic cores respectively.

Simulation of the finite element model, calculation of stress distributions, and the processing were performed using ABAQUS/CAE (Professional Version 6.10, Simulia, Valley St., Providence, USA). Stress patterns were obtained from the centrally located nodes on the surfaces of the veneer, ceramic core, cement, and dentin, and spanning from the cervical line of the buccal surface to the cervical line of the palatal surface (Fig. 4). Von Mises stress, maximum principal stress, minimum principal stress, and shear stress distribution were collected in each component and at veneer-ceramic core-cement-dentin interfaces (X, Y, and Z).

RESULTS

The FEA program almost always registers high stresses at the loading point, especially when a point load was applied. Figure 5 shows that the highest von Mises stress levels were observed within all structures under loading in all the models.

Von Mises stress developed from the loading site on the crown and slightly decreased toward the inner parts of the tooth, registering these maximum stress levels: 139.7 MPa (Model A), 139.3 MPa (Model B), 139.5 MPa (Model C), 139.6 MPa (Model D), 109.9 MPa (Model E), 109.8 MPa (Model F), 109.8 MPa (Model G), and 61.5 MPa (Model H) (Fig. 5). Reduction in average von Mises stress values under oblique loading was observed in graded multilayered ceramic cores (Models E to G), compared with the homogenous zirconia ceramic core (Model A) without alumina.

Figure 6 shows the von Mises stress distributions in...

![Fig. 3](Image)

**Fig. 3** Application of static load in oblique direction.

![Fig. 4](Image)

**Fig. 4** Schematic illustration of stress measurement.

<table>
<thead>
<tr>
<th>No</th>
<th>Tissue/Materials</th>
<th>Young’s Modulus (GPa)</th>
<th>Poisson’s Ratio</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Isotropic Enamel</td>
<td>80</td>
<td>0.32</td>
<td>22</td>
</tr>
<tr>
<td>2</td>
<td>Dentin</td>
<td>18.6</td>
<td>0.31</td>
<td>27</td>
</tr>
<tr>
<td>3</td>
<td>Periodontal ligament</td>
<td>0.689</td>
<td>0.49</td>
<td>22</td>
</tr>
<tr>
<td>4</td>
<td>Spongy Bone</td>
<td>0.345</td>
<td>0.30</td>
<td>22</td>
</tr>
<tr>
<td>5</td>
<td>Compact Bone</td>
<td>13.8</td>
<td>0.26</td>
<td>27</td>
</tr>
<tr>
<td>6</td>
<td>Veneering</td>
<td>70</td>
<td>0.28</td>
<td>28</td>
</tr>
<tr>
<td>7</td>
<td>Zirconia</td>
<td>210</td>
<td>0.30</td>
<td>11</td>
</tr>
<tr>
<td>8</td>
<td>Alumina</td>
<td>400</td>
<td>0.30</td>
<td>29</td>
</tr>
<tr>
<td>9</td>
<td>Luting Cement</td>
<td>15.9</td>
<td>0.33</td>
<td>30</td>
</tr>
</tbody>
</table>
an obliquely loaded tooth model restored with different types of ceramic cores (Models A to G). Maximum von Mises stress was concentrated at the load application point on the crown and spread to the middle of the occlusal surface. Maximum von Mises stress levels were observed directly below the load application point in both the veneer and ceramic core. Highest stress levels were observed in the ceramic core region in contact with the cement layer. Increased stress levels were also observed at the marginal regions of the ceramic core, including the cervical and proximal regions. Among the models, higher von Mises stress levels were observed in the ceramic core of Models A to D, and lower von Mises stress levels in the graded multilayered ceramic core (Models E to G). Moving inwards toward the cement layer and tooth dentin saw a progressive decrease in stress level (Fig. 6).

Maximum tensile stress levels (maximum principal stress) were observed in the veneer and ceramic core of Models A to D. However, lower tensile stress levels were observed in the graded multilayered ceramic core (Models E to G) (Fig. 7). Additionally, maximum compressive stress levels were observed in the veneer and ceramic core of Models A to D. However, lower compressive stress levels (minimum principal stress) were observed in the graded multilayered ceramic core (Models E to G) (Fig. 8).

Shear stress at the veneer-core interface of graded multilayered models (Models E and F) was lower than in the single-layer models (Models A to D) (Fig. 9). Similarly, shear stress at the core-cement interface of...
Fig. 7  Tensile stress distributions in the veneer, ceramic core, cement, and dentin of all models.

Fig. 8  Compressive stress distributions in the veneer, ceramic core, cement, and dentin of all models.

Fig. 9  Shear stress distributions within veneer-core-cement-dentin interfaces.
Fig. 10 Shear stress distributions at veneer-core-cement-dentin interfaces in all models.

graded multilayered models (Models E and F) was lower than in the single-layer models (Models A to D).

High stress levels were observed directly below the loading site in the veneer and ceramic core regions (Fig. 10a). Higher stress levels were observed at the ceramic core region in contact with the cement layer (Fig. 10b). Increased stress levels were also observed at the marginal regions of the ceramic core, including the cervical and proximal regions. Stress in dentin was considerably lower in Models E to G than in Models A to D (Fig. 10c).

DISCUSSIONS

In the present study, FE stress analysis suggested that the subsurface region under the occlusal surface of ceramic crown, near the crown-cement interface, was subjected to the largest tensile stress. The fracture initiation sites of dental ceramic crowns are primarily controlled by the location and size of the critical flaw. Campbell reported that the support of veneer porcelain was directly related to the Young’s modulus and not to the strength of the substructure material. According to Scherrer and de Rijk, the increased length of an all-ceramic crown on a die with an elastic modulus of 3 GPa increased the resistance to fracture, while Derand reported that crown length played only a small role in fracture resistance.

With single-layer ceramic cores, maximum tensile stress occurred either at the outer surface adjacent to the loading site or in the inner surface of the ceramic core. Location of maximum tensile stress strongly depended on the Young’s modulus of the supporting substrate. In the current study, when the substrate which simulated dentin had a Young’s modulus of 18 GPa, maximum principal stress occurred at the outer surface adjacent to the loading site. This high stress level was the dominant cause of failure. With multilayered ceramic cores, maximum principal stress was located in the subsurface region below the loading site, near ceramic core-cement interface. The presence of such a high bending stress level in a non-rigid supporting substrate (material with low Young’s modulus) became the dominant reason which caused fracture.

In a ceramic crown restoration, the supporting substrate of the remaining dental structure is dentin with a Young’s modulus of 18 GPa. A more probable fracture site would be located on the inner surface of the dental crown instead of the outer surface near the biting area. This finding agreed with the numerous investigations on dental crown fractures conducted by Thompson et al., Anusavice and Hojjatie, and Kelly et al.

In each model, stress level in the dentin core was of extremely low magnitude (Models A to H). In Models E to H, stress level was almost neutral and which was lower than that in Models A to D. This phenomenon suggested that the ceramic core “protected” the dentin core from bearing loads or stresses of significant magnitude. In addition, the ceramic core with significantly higher elastic modulus than the abutment material bore the full brunt of the applied compressive load. The stiff ceramic core material effectively transferred the compressive load to the base of the tooth through the chamfer margin. This compression diversion around the dentin core caused the latter to experience relatively low compressive stress at approximately 0 MPa to 20 MPa. A higher elastic modulus would imply a greater role in absorbing the applied load and diverting it around the tooth abutment. The marginal area should be cautiously designed because increased tensile stress, although not critical, occurred in this region.

CONCLUSIONS

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

1. Compared with single-layer ceramic cores (Models A, B, C, D), FGDCs (Models E, F, G) reduced the levels of von Mises stress, tensile stress, and compressive stress within the tooth which was restored with a multilayered ceramic core.

2. Compared with single-layer ceramic cores (Models A, B, C, D), FGDCs (Models E, F, G) reduced shear stress at veneer-ceramic core-cement-dentin interfaces.
ACKNOWLEDGMENT

This investigation was supported by grants from the University of Malaya, IPPP (PV020-2011B (IPPP) and RG512-13HTM (UMR)). In addition, this study was partially supported by a High Impact Research (HIR) grant from the Ministry of Higher Education, Malaysia (HIR-MOHE-16001-00-D000001).

REFERENCES


