# Evaluation of Fracture Resistance and Failure Risks of Posterior Partial Coverage Restorations

DEAN E. KOIS, DMD, MSD\*, VARA ISVILANONDA, BEng, MSME<sup>†</sup>, YADA CHAIYABUTR, DDS, MSD, DSc<sup>‡</sup>, JOHN C. KOIS, DMD, MSD\*<sup>§</sup>

## ABSTRACT

**Statement of Problem:** Interest in posterior partial coverage restorations has increased because these restorations provide a more conservative treatment option than traditional cohesively based restorations; however, material selection has been a controversial topic in the current literature.

**Purpose:** To evaluate the fracture resistance of posterior partial coverage restorations restored with different materials, examine their stress distribution, and calculate failure risks using three-dimensional (3D) finite element analysis. **Methods:** Sixty extracted third molar teeth received 2-mm occlusal reduction maintaining cusp steepness of 45 degrees relative to occlusal surface. Teeth were allocated into four groups (N = 15) and restored with different materials: feldspathic ceramic, leucite-reinforced ceramic, lithium disilicate-reinforced ceramic (EMX), or indirect resin-based composite (COM). Restorations were luted with resin cement and submitted to compressive loads (Instron Corp, Norwood, MA, USA). The data were analyzed with one-way analysis of variance, followed by Tukey's HSD tests. A 3D finite element model of posterior partial coverage restorations was developed and validated. The model was used to approximate the maximum principal stress in each of the materials under a 100-N static vertical compression at the occlusal surface of the tooth. The risk of restoration failure was quantified and compared among the four different materials.

**Results:** Group EMX had fracture resistance significantly higher than other testing groups. Group COM presented the most extensive fractures involving tooth and root structures. When compared with the other materials, group EMX exhibited higher stress concentration; however, the failure risk of the restoration was lower.

**Conclusions:** Fracture resistance and failure risks of posterior partial coverage restorations are significantly influenced by material selection.

## **CLINICAL SIGNIFICANCE**

Many restorative materials have been advocated for partial coverage restorations. It is essential to ensure that restorative materials have sufficient strength to support occlusal forces and, in case of fracture, the remaining tooth structure is not compromised or placed at risk. This study revealed that all-ceramic materials had high incidences of fractures involving the materials themselves, whereas the predominant failure of resin-based composite involved the tooth structure in a catastrophic manner.

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<sup>\*</sup>Private Practice, Seattle, WA, USA

<sup>&</sup>lt;sup>†</sup>Graduate Student, Department of Mechanical Engineering, College of Engineering, University of Washington, Seattle, WA, USA <sup>‡</sup>Affiliate Instructor, Department of Restorative Dentistry, School of Dentistry, University of Washington, Seattle, WA, USA <sup>§</sup>Affiliate Professor, Department of Restorative Dentistry, School of Dentistry, University of Washington, Seattle, WA, USA

## INTRODUCTION

In clinical situations, an ideal amount of existing tooth structure may not be present when restoring compromised teeth. Numerous restorative challenges are encountered when designing restorations for teeth that have lost substantial structure whether through caries, fractures, or the combined effects of occlusal attrition and erosion. Restorative materials have certain dimensional requirements for strength and in many cases require the removal of additional sound tooth structure to provide a successful restoration. This could be considered a major cause for tooth fracture and/or pulpally related sequelae. As the width and the depth of the tooth preparation increases, the strength of the remaining tooth structure diminishes.<sup>1–3</sup> The use of tooth-colored partial coverage restorations-such as inlays or onlays-have increased because these restorative designs provide a conservative and esthetic option that requires minimal tooth preparation, thus preserving the tooth's inherent structural integrity.4-6

Several restorative materials have been used to fabricate partial coverage restorations, including cast metal, all-ceramic, and resin-based composites. The use of cast metal restorations has been decreasing over the past decade and has given way to tooth-colored restorations because of esthetic demands and the rising costs of precious metals. Glass ceramics (feldspathic), particle-filled glass ceramics (leucite-reinforced and lithium disilicate-reinforced), and resin-based composites have become the materials of choice. However, controversy exists as to which material provides the most strength to support occlusal forces.

Previous studies revealed that feldspathic ceramics provide excellent esthetic characteristics with a relatively high survival rate between 84.7% and 96.6% during observation periods up to 6 years<sup>7–9</sup>; however, the fabrication process (sintering) is laboratory dependent. Microporosities and inhomogeneties between the particles can be created during the sintering process, which can initiate crack formation, thus affecting the long-term performance of the restorations. Physical properties of glass ceramics have improved by incorporating leucite and lithium disilicate particles. These particle-filled glass ceramics can be fabricated by heat-pressing, which was developed to overcome inhomogeneities and porosity during the sintering process.<sup>10</sup> Previous studies revealed a high survival rate of particle-filled ceramics between 92% and 97% during observation periods up to 5 years,<sup>11–15</sup> and 94% to 98% at the 7- and 8-year intervals, respectively.<sup>16</sup>

In addition to the traditional sintering and heat-pressed techniques, computer-aided manufacturing fabrication has been available in the market. With similar material composition, glass ceramic blocks which are prefabricated under optimum and controlled conditions obtain more uniform ceramic quality without the inevitable material variations seen in manually produced restorations.<sup>17,18</sup> Previous studies reported short-term clinical survival rate at 95% after an observation period of 5 years.<sup>19–21</sup> Other studies with long-term observation periods revealed the survival rate between 84.9% and 90% at 7 to 10 years.<sup>22,23</sup> Despite the high survival rate of these restorations, marginal discrepancy may arise from overgrinding and chipping of thin porcelain margins due to the brittle nature of the material and milling vibration.<sup>24</sup>

In addition to glass ceramic, indirect resin-based composite has also demonstrated acceptable clinical performance and is considered as an alternative material for posterior partial coverage restoration.<sup>25,26</sup>

Indirect fabrication techniques are recommended when large restorations are required to allow the composites to be placed in the tooth preparations with minimal shrinkage.<sup>27</sup> Several new indirect resin-based composites were introduced into the market. These composites have increased the percentage by volume of inorganic fillers (approximately 66%) in the materials, which improves their mechanical properties compared with traditional indirect resin-based composites.<sup>28</sup> It has been postulated that their relatively low modulus of elasticity allows them to absorb some occlusal stresses, thus acting as a shock absorber.<sup>27</sup> Previous studies revealed that resin-based composite partial coverage restorations provided better load fatigue resistance under high load when compared with all-ceramic partial coverage restorations.<sup>29,30</sup> However, several studies have demonstrated problems on marginal failure, bonding interface, and wear resistance of the restorations after placement.<sup>31–33</sup>

It has been reported that materials or interfaces normally fail because of repeated loading from stresses that are too small to provoke spontaneous failures after only one application. To achieve a better understanding of the in vivo behavior and clinical performance of adhesively retained restorations, an in vitro fatigue test has been suggested.<sup>34</sup> However, the high costs of restoration specimens, a long time scale, and machine-running time might be restrictive. Fracture strength values that are most widely used and often relied upon as indicators of structural performance for dental materials might be considered to compare the fracture resistance among different restorative materials.

Load distribution is an essential restorative design component but has proven difficult to study because of the complexity of dental restorations. Strength is more of a conditional property rather than an inherent material property. In the present study, finite element analysis (FEA) was used to investigate the effect of elastic modulus and Possion's ratio on the risk of partial coverage restoration failure.

FEA has been used as an alternative tool in biomechanics research. In dentistry, several previous studies used FEA to determine how geometry, loading, material properties, and stress distribution influence dental restoration survival.<sup>35–39</sup> The risk of failure in restorations can be quantified by dividing the maximum stress of the restoration design by the strength of the material. Relative safety factor is defined as an inverse of the risk of failure. Relative safety factor is widely used in engineering design to indicate any extra capacity above the expected loads that a structure has before reaching its failure point.<sup>40,41</sup> In this model, a relative safety factor below 1.0 indicates biomechanical risk in the restoration design. The greater the value, the lower the risk of failure. Knowledge regarding the risk of failure or the relative safety factor in restorative materials will assist in enhancing the clinician's ability to develop the most appropriate treatment plan and communicate realistic expectations to their patient.

The purpose of the present study was to evaluate the fracture resistance of posterior partial coverage o restorations restored with different materials, examine their stress distribution, and calculate failure risks using three-dimensional (3D) FEA. The first null hypothesis was that the fracture resistance of posterior partial coverage would not be affected by the restorative material. The second null hypothesis was that the failure risks of posterior partial coverage restorations are not determined by their restorative materials. A biomechanical risk of failure for each type of restoration was assessed.

## MATERIALS AND METHODS

#### Determining Fracture Resistance

Sixty extracted human third molars were selected. Immediately following extraction, the teeth were cleaned of surface debris and disinfected in 0.5% sodium hypochlorite. Teeth were then selected on the criteria that they were intact and lacked cracks or fractures in the crown, contained no evidence of caries, and had no prior restorations.

The bucco-lingual, mesio-distal, and occluso-cervical dimensions of the teeth were measured using a digimatic caliper accurate to within 0.01 mm (Mitutoyo series 551, Mitutoyo USA, Aurora, IL, USA). Three measurements were made at the greatest bucco-lingual, mesio-distal, and occluso-cervical widths of the specimens, and the averages were determined. Overall, tooth sizes were within a 10% deviation. Extracted human molar that were used may have a disadvantage in the great variation in age and quality, and might make the bonded interface difficult to standardize as samples. In the present study, using the higher number of specimens tested (N = 15 in each group) may give more precise failure results for a partial coverage restoration system.

The teeth were attached to a dental surveyor (J. M. Ney Co., Bloomfield, CT, USA) rod using a sticky wax (Kerr sticky wax, Kerr, Orange, CA, USA) on a vertically prepared surface, so that the long axis of the teeth would be parallel to the surveyor rod. The teeth were lowered into a copper cylinder, positioned in the center of the cylinder with the buccal cementoenamel junction 3 mm above the top of the coppermounting cylinder. Premixed autopolymerizing resin (Pattern Resin, GC America, Scottsdale, AZ, USA) was injected into the cylinder until it was completely full. After acrylic resin polymerization, the dental surveyor rod was detached and the specimens stored in distilled water at room temperature.

The mounted teeth received a 2-mm occlusal reduction maintaining cusp steepness of 45 degrees relative to the occlusal surface<sup>42</sup> (330MWV, KS7, KS0, KS0F, Brasseler, Savannah, GA, USA) using a high-speed electric handpiece (KaVo Dental Corp., Lake Zurich, IL, USA) and diamond rotary cutting instrument and carbide burs under cool water irrigation. Teeth were then allocated into four groups to be restored with four different materials: feldspathic ceramic (FEL) (Reflex, Wieland Dental System, Milford, CT, USA); leucite-reinforced ceramic (EMP) (IPS Empress, Ivoclar Vivadent, Schaan, Leichtenstein, Germany); lithium disilicate-reinforced ceramic (EMX) (IPS e.Max, Ivoclar Vivadent); and indirect laboratory-processed resin-based composite (COM) (Radica, Dentsply, York, PA, USA). All materials used were manipulated in accordance with the manufacturers' recommendations.

An impression of each prepared tooth was made with light- and heavy-body polyvinyl siloxane impression material (Impressiv, Cosmedent, Chicago, IL, USA) using a dual-phase single-stage technique according to the manufacturer's instructions. After 24 hours the impressions were poured with a vacuum-mixed die stone (ETI Empire Direct, Anaheim, CA, USA) and allowed to set for 24 hours. The stone cast was recovered and inspected for any defects under (×10) magnification. For the ceramic specimens, two coats of die spacer (Rem-e-die, Ivoclar Vivadent) were utilized. For group FEL, ceramic powders were mixed with deionized water; vibrated and excess water was removed with absorbent paper to condense the ceramic. All specimens were fired according to the manufacturer's instructions in a programmable vacuum furnace (Dekema Austromat 3001, Dekema, Frankfurt, Germany) under two firing cycles at 905°C with a ramp rate of 75 seconds and a hold time of 120 seconds (sintering), and at 880°C with a ramp rate of 75 seconds (glazing).

For group EMP and group EMX, these ceramics were pressed according to the manufacturer's protocol. A partial occlusal coverage restoration was created in wax. After waxing, each pattern was transferred back to its working die and the pattern margins refined under (×10) magnification. Sprue formers were attached to the patterns with four patterns placed into each investment ring. The burnout furnace cycle (Grobet<sup>™</sup> USA, www.grobetusa.com) used a two-stage burnout at 255°C for 30 minutes, and up to 850°C with a hold time of 60 minutes. The ceramic investments were transferred to the P300 ceramic furnace (Ivoclar Vivadent). A pressable ceramic (IPS Empress, Ivoclar Vivadent) was utilized to cast the restorations with VP1989/4 ingot material using a temperature of 915°C and a holding time of 20 minutes. Divestment was performed using 50-µm aluminum oxide airborne particle abrasion at 50 psi.

For group COM, partial coverage indirect laboratory-processed resin-based composite were made according to the manufacturer's instructions. The silicone putty matrix (Radica silicone putty, Dentsply) was applied over the waxed restoration. The silicone putty matrix was removed after hardening, and the waxed pattern was removed after hardening, and the waxed pattern was removed from the stone cast. The resin-based composite syringe was heated at 60°C for 10 minutes in the warmer machine (Radica Syringe Heater, Dentsply) prior to injection into the silicone putty matrix. The silicone putty matrix with warm resin-based composite was placed over the stone cast. The remaining excess of materials was removed with a #12 scalpel blade (Bard Parker, Franklin Lakes, NJ, USA). The stone cast was placed into the curing unit (Enterra VLC Curing Unit, Dentsply) for 5 minutes for resin complete polymerization process. All restoration margins were polished with fine polishing discs (Sof-Lex, 3M ESPE, St. Paul, MN, USA). The liquid resin sealer (VLC Sealer Cure, Dentsply) was applied on the surface, and finished restorations were placed into the curing unit for 2 minutes to complete the liquid resin polymerization process.

Specimen cementation included mechanical debridement using aluminous oxide abrasion (PrepStart, Danville Engineering, San Ramon, CA, USA) with a particle size of 27 µm at 40 psi at a distance of 2 mm from the tooth surfaces.<sup>43</sup> The prepared teeth were etched for 15 seconds with 37% phosphoric acid (Scotchbond Etchant gel, 3M ESPE), rinsed for 10 seconds, and dried sparingly. The bonding agent (One-step, Bisco Inc., Schaumburg, IL, USA) was applied to specimens in two coats for 15 seconds and gently air-dried. The intaglio surfaces of the ceramic specimens were treated with 9.5% hydrofluoric acid (Porcelain Etching Gel, Ultradent, Jordan, UT, USA) for 90 seconds then silanated with ceramic primer (Scotch Bond Primer, 3M ESPE).

All specimens were luted with dual-polymerizing composite resin cement (RelyX ARC, 3M ESPE). The restorations were held in place for the duration of the manufacturer's recommended setting time under finger pressure and simultaneously photopolymerized with a light intensity of 480 nm and a power of 1,100 mW/cm<sup>2</sup>  $(\pm 10\%)$  (Optilux 501, Kerr) for a 5-second burst. The cement excess was then removed, followed by full polymerization for 40 seconds on all surfaces. All restoration margins were polished with fine polishing discs (Sof-Lex, 3M ESPE). The bonded specimens were stored in water at room temperature prior to the compressive load testing. Each specimen was secured vertically on a metal holder in a universal testing machine (Model 5585H, Instron Corp., Norwood, MA, USA) equipped with a 1-kN load cell. All of the specimens were tightened and stabilized. In order for strength testing to be clinically relevant, it is generally recommended that the mode of loading be chosen to closely simulate the actual component in service.<sup>44,45</sup> In the present study, a 6 mm in diameter of stainless steel

ball, its size similar to that of a molar cusp, was positioned on the central fossa of the occlusal surface of the restoration to simulate an occusal contact point of an antagonist tooth<sup>46</sup> (Figure 1).

A load was applied via displacement control at 0.05 mm/minute until catastrophic failure occurred. The ultimate load to failure was recorded in newtons (N), and the means and standard deviations were calculated. The fractured surfaces were then examined to determine the mode of failure. The catastrophic failure was classified in accordance with one of the following criteria: a cohesive failure not involving tooth (Type I), a cohesive failure involving any interface (Type II), a cohesive failure involving the crown (root preserved) (Type III), and a fracture involving root (Type IV). All restorations were inspected under (×10) magnification. Parametric statistical analyses were performed at a 95% confidence interval using statistical software (SAS V.9.1, SAS Institute, Cary, NC, USA).



**FIGURE I.** Representative photograph of specimen test under compressive load.

Groups were analyzed using a one-way analysis of variance (ANOVA), followed by Tukey's HSD multiple comparison test to evaluate differences among the testing groups.

#### Determining Failure Risks

The stress distribution in the tooth-restoration complex under a static load application was evaluated using FEA. A mandibular molar was imaged using micro-computed tomography (Skyscan1076, Skyscan, Kontich, Belgium), pixel spacing 0.036 mm. The scan was segmented (Simpleware, Exeter, UK) to obtain a 3D solid model of enamel and dentin (Figure 2A).

The model was imported into ANSYS ICEM CFD (ANSYS Inc., Canonsburg, PA, USA) where the tooth preparation was generated. A 2-mm occlusal reduction



**FIGURE 2.** Representative photographs of: A, threedimensional rendering of the normal tooth; B, internal contours and a parametric cutting plane to generate tooth preparation; and C, finite element fine mesh of numerical model showing of static load application. plane was modeled by locating three points on the sagittal plane of the tooth: the most superior point on the medial and lateral cusps and a deepest point in grooves. The selected points were translated 2 mm vertically downward and projected to the occlusal plane. A V-shaped line was defined from three points and extruded in the mediolateral direction to locate an interface between crown and luting agent. This surface was duplicated and translated 0.5 mm vertically downward to define an interface between luting agent and the inferior structure of the preparation (enamel and dentin) (Figure 2B).

An interface between bone and dentin was estimated by positioning the tooth in the center of the cylindrical tube, with the buccal cementoenamel junction 3 mm above the top of cylinder. Mesh convergence analysis was performed on a normal tooth model. All parts were meshed using linear tetrahedral elements (global element size of 0.35 mm, 0.15 mm for luting agent to capture geometric details), and the completed model consisted of 5 parts: enamel, dentin, bone in cylindrical tube, restorative materials, and luting agent. The finite element (FE) mesh was preprocessed in LS-Prepost (Livermore Software, Livermore, CA, USA). The material properties applied to the various materials were obtained from the literature and are listed in Table 1. To simplify the FEA, homogeneous, linear elastic, and isotropic materials were used. The periodontal ligament and actual anatomy of the bone were not considered. An ideal adhesive interface between material interfaces was assumed.

Four different restorative material properties were studied. Perfect adhesion was assumed between the structures (restorative materials and luting agent, luting agent and tooth structure, enamel and dentin, and dentin and bone). Nodal degrees of freedom (DOFs) were restricted in all directions at the external lateral outline and base of the cylinder. A vertical 100-N linear ramp-and-hold force (0.001-second ramp and 0.0005-second hold) was applied on the center occlusal surface via a 6-mm diameter rigid sphere (Figure 2C). The force applied falls within the limits of normal human physiological chewing forces around posterior teeth, which ranges from 2 to 150 N.<sup>47,48</sup>

Materials	Elastic modulus (E) (GPa)	Poisson's ratio (v)	Density (ρ) (g/cm³)
Enamel	84.10	0.30	2.92
Dentin	18.60	0.31	2.65
Bone	13.80	0.26	1.85
Feldspathic ceramic	65.00	0.19	1.00
Leucite-reinforced ceramic	65.00	0.23	1.01
Lithium disilicate-reinforced ceramic	95.00	0.24	2.50
Resin-based composite	16.60	0.24	2.10
Resin luting cement	8.30	0.35	1.10

TABLE I. Material pro	operties used in the finite	element analysis (FEA	<ul> <li>elastic modulus (E),</li> </ul>	, Poisson's ratio (v), and	density $(\rho)$
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The sphere was allowed to move in all six DOFs. To ensure that the model reached equilibrium at a reasonable solving time, global damping at 25% of the critical damping (System Damping Coefficients [VALDMP] = 10,000) of the system was used. The model was solved in LS-DYNA explicit (Livermore Software). Model prediction was qualitatively validated by comparing the location of the maximum tensile stresses in crown, cement, and tooth structure with the failure site from the experiment. Ten elements that revealed the highest maximum principal tensile stresses were located (excluding compression and stress singularity near the sphere-crown contact, values taken at an integration point of each element), and an average value was calculated for each material. The risk of restoration failure and the risk of cement failure were calculated by dividing the maximum principals' stress by the material's tensile strength. Relative safety factor of the materials was defined as an inverse of failure risks.

## RESULTS

The mean fracture resistance (standard deviation [SD]) of all groups, results of Tukey (p < 0.05) multiple comparison, and mode of failure are presented in Table 2. Group EMX revealed the highest mean fracture resistance values relative to other testing groups. One-way ANOVA revealed the significant differences

**TABLE 2.** Mean (standard deviation [SD]) values of fracture resistance and the distribution of failure modes from the groups. Statistically significant difference (p < 0.05) is indicated by different superscript symbols

Group	Mean (Newton)	Mode of failure			
		1	Ш	Ш	IV
FEL	1,703 (256) <sup>‡</sup>	10	2	3	0
EMP	2,082 (292)†	7	4	4	0
EMX	2,522 (335)*	2	9	4	0
COM	1,614 (250) <sup>‡</sup>	0	I	3	

FEL=feldspathic ceramic; EMP=leucite-reinforced ceramic; EMX=lithium disilicate-reinforced ceramic; COM=indirect resin-based composite.

among the groups. The fracture resistance of group EMX was significantly higher than those groups of FEL, EMP, and COM (p < 0.001). There was a significant difference in fracture resistance between group EMX and group EMP (p < 0.05). Group EMP had significant differences in fracture resistance compared with group FEL (p < 0.05), whereas group FEL had no significant differences in fracture resistance compared with group COM (p = 0.832).

Most of the ceramic specimens presented a high incidence of fractures involving only the ceramic materials (Type I and Type II), whereas in group COM fractures were more catastrophic, and 74% of fractures involved roots of the specimens (Type IV) (Figure 3).

The maximum principal tensile stresses in the simulated models on the restorative materials and luting agents are presented in (Table 3). The highest tensile stress in the ceramic specimens was predicted in group EMX (33.95 MPa), followed by group EMP (29.36 MPa), group FEL (28.77 MPa), and group COM (14.39 MPa), respectively. At the superior surface of restorative materials, the highest concentration of tensile stresses was in the center of the occlusal surface. Stress concentrations decreased moving laterally away from the center (Figure 4A). The principal stress distributions at the inferior surface of the restorative materials are shown in Figure 4B. Most tensile stresses were transferred from the contact point of load application. The highest stresses in the adhesive layer were found at the enamel region on the edge of restoration. Stress distribution and magnitude in the luting agent were similar in all tested models (mean 2.90 MPa, SD 0.19 MPa) (Figures 4C and D). Stresses within the tooth structure were lower in ceramic specimens: group EMX (enamel, 9.55 MPa; dentin, 2.74 MPa), group EMP (enamel, 10.77 MPa; dentin, 3.15 MPa), and group FEL (enamel, 10.71 MPa; dentin, 3.14 MPa). In contrast, the resin-based composite group revealed a high stress concentration in tooth structure (enamel, 17.77 MPa; dentin, 5.08 MPa) (Figure 4E). Group EMX had a lower failure risk of restoration (0.08) when compared with other materials (range 0.14-0.29). There was no sign of material failure predicted at the average occlusal force



**FIGURE 3.** Representative photograph examples of specimen failure: A, feldspathic ceramic fracture, crack initial along the central fossa (Type I); B, lithium disilicate-reinforced ceramic fracture, the fracture involving an adhesive interface (Type II); C, leucite-reinforced ceramic fracture, the fracture involving the crown (Type III); and D, indirect resin-based composite fracture, the fracture involving root (Type IV).

**TABLE 3.** Mean (standard deviation [SD]) of maximum principal stress ( $\sigma$ max) from 10 elements, failure risk of materials (RF), and relative safety factor (RSAF) of materials. Note that the risk of failure was calculated by dividing the maximum principal stress by material's tensile strength (TS). The RSAF below 1.0 indicates biomechanical risk in the restoration design. The greater the value, the lower the risk of failure

Group	Restorative materials				Luting agent			
	σmax (MPa)	TS (MPa)	RF	RSAF	σmax (MPa)	TS (MPa)	RF	RSAF
FEL	28.77 (1.44)	100	0.29	3.48	2.88 (0.17)	77.6	0.04	26.94
EMP	29.36 (1.50)	160	0.18	5.45	2.89 (0.17)	77.6	0.04	26.85
EMX	33.95 (1.86)	400	0.08	11.78	2.67 (0.19)	77.6	0.03	29.06
COM	14.39 (0.81)	100	0.14	6.95	3.14 (0.18)	77.6	0.04	24.71

FEL=feldspathic ceramic; EMP=leucite-reinforced ceramic; EMX=lithium disilicate-reinforced ceramic; COM=indirect resin-based composite.

of 100 N in all tested models as the relative safety factors were above 1.0.

## DISCUSSION

The results of the present study support the rejection of the first null hypothesis because the fracture resistance of posterior partial coverage restorations is affected by the choice of restorative materials. The results revealed that lithium disilicate-reinforced ceramic had the highest fracture resistance among the glass ceramic systems tested. One possible explanation could be that the increased crystallinity of lithium disilicate-reinforced ceramics provides a tighter interlocking matrix in its structure, which consequently improves the strength and fracture toughness, compared with other ceramic systems.<sup>49–52</sup>

In general, the amount of the remaining tooth structure significantly influenced the stress distribution and mode of failure in the tooth-restoration system. Because partial coverage restorations require minimal tooth preparation and most of the residual tooth structure remains, it is possible that occlusal load would pass entirely through the bulk of the restorative material, and the highest stress concentration would appear at the level of the material. It would then expect ceramic materials with more favorable mechanical properties to perform better and be more fracture resistant. The results were confirmed by mode of failure, which revealed a high incidence of fractures involving ceramic material itself: 67% in group FEL, 53% in group EMP, and 13% in group of EMX, respectively. For clinical situations where fracture resistance is more critical, these results support the use of lithium disilicate-reinforced ceramic when using ceramic as a restorative material for partial coverage restorations.

The FEA demonstrated that the type of restorative material influenced both the location and the level of peak stresses in the restorative materials and remaining tooth structure; therefore, the second null hypotheses tested was rejected. Maximum principal stresses in the remaining tooth structure could be influenced by the elastic modulus of the restorative materials. Ceramic materials with a high elastic modulus (65–95 GPa) behave more rigidly, displaying little deformation and tend to reinforce the remaining tooth structure. The risk of tooth fracture may be minimized because the restorative material is likely to fracture before the tooth. Conversely, indirect resin-based composite, because of its lower elasticity modulus (approximately 16-20 GPa), showed more flexibility and needs reinforcement from the remaining tooth structure for rigidity. When the indirect composite material was used, more occlusal force was transferred to the remaining tooth structure, which resulted in greater risk of tooth fracture. The results were confirmed by mode of failure, which revealed a high incidence of fracture involving tooth structure in group COM (73%). As a result, indirect resin-based composite material may have a more



**FIGURE 4.** Surface maximum principal stress distribution (plot of average nodal values): A, occlusal surface; B, inferior surface of restorative materials (rotated 180 degrees from A); C, superior surface of the luting agent layer; D, inferior surface of the luting agent (rotated 180 degrees from C); and E, the remaining tooth structure. Note that from left to right are, feldspathic ceramic, leucite-reinforced ceramic, lithium disilicate-reinforced ceramic, and resin-based composite.

limited application. A similar mechanical behavior of stress transfer has been previously observed in full-coverage restorations.<sup>53,54</sup>

Sharp line angles or sudden dimensional changes should be avoided in preparation design to maintain consistent stress concentration. The FEA demonstrated high stress concentrations in the central occlusal of the prepared teeth, where the two planes of occlusal surface intersected.

Several assumptions posed limitations in the study. The overall thickness of restorative materials (2.0 mm) was slightly higher than the minimum recommended by the manufacturer (1.5 mm) for posterior teeth. Because restorative material thickness greatly influences the fracture load, the resulting loads in the present study are probably higher than would result from the recommended clinical thicknesses. The test methods used for this study also do not consider slow crack growth within the ceramic material. In this study design, the specimens were forced to fail from surface-initiated fractures. Further investigations should consider a fatigue load study, as these phenomena and its relationship likely influence ceramic fractures in clinical service.

# CONCLUSIONS

Within the limitation of the study, the fracture resistance and failure risks of posterior partial coverage restorations were significantly influenced by material selection. Lithium disilicate-reinforced ceramic had higher fracture resistance and stress concentration; however, the failure risks of restoration were lower than other materials. All-ceramic materials revealed high incidence of fractures involving the material itself, whereas the predominant failure of resin-based composite involved more to the remaining tooth structure.

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Reprint requests: Yada Chaiyabutr; DDS, MSD, DSc, 1001 Fairview Avenue N, Suite 2200, Seattle, WA 98109, USA; Tel.: 206-621-5310; email: yada@koiscenter:com

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