Finite Element Stress Analysis of Indirect Restorations Prepared in Cavity Bases

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The objective of this study was to analyze the distribution of tensile stresses in indirect restorations prepared in several composite cavity bases. Elastic moduli of 20 materials were measured by nanoindentation technique for finite element analysis. Axisymmetric models of posterior onlays were constructed using combinations of two onlay materials and three cavity base materials. Thickness of resin cement was 50 μm . A vertical load of 95.5 N was applied on the cusp tip. Maximum stress of 18.1 MPa was found in the model consisting of a ceramic onlay and a flowable resin composite base. It was also found that tensile stress increased as the area of the base having a lower elastic modulus became wider. Base materials having higher elastic moduli were determined to be suitable as cavity base materials for posterior restorations.

Keywords: Finite element analysis, Indirect restoration, Cavity base

INTRODUCTION

Rapid advances in enamel and dentin adhesive technology have significantly changed the landscape of caries treatment. Since the establishment of procedures for minimal caries removal and adhesive resin composite restorations¹⁾, adhesion has played an unequivocally pivotal role in minimal intervention dentistry^{2,3)}. As a result, numerous dental polymeric materials have been developed, such that direct adhesive restorations have performed well in many clinical cases which used to be restored indirectly.

However, while techniques for minimizing tooth reduction has been utilized by and therefore benefited direct adhesive restorations^{3,4)}, this is not the optimistic case with indirect restorations—despite the emergence of many adhesive materials, such as resin cements. As a result, conventional indirect restorative procedures, which result in excessive tooth reduction, continue to be performed clinically. For example, in the case of a secondary caries at the gingival margin on the proximal surface of a Class II inlay, reparation of cavity must be done following caries removal and cavity margins are prepared in the tooth structure. This procedure then leads to substantial reduction in tooth structure because the whole cavity has to be prepared without any undercuts. In addition, subgingival location of the preparation margin that frequently occurs in such preparations makes impression taking or moisture control for cementation more difficult.

Compared to cast metal restorations, indirect restorative procedures require removal of large amounts of tooth substance due to the basic requirements of resistance form and convenience form. To minimize the sacrifice of tooth structure, a previous

report proposed a technique whereby part of the cavity margin of an amalgam restoration was placed in a glass ionomer cement cavity base used to seal the dentin surface after caries removal⁴⁾. Moreover, another study reported that the placement of preparation margins in a resin composite base minimized microleakage and enhanced adaptation of all-ceramic crowns⁵⁾. It was thus clear that preparation of the entire cavity in adhesive cavity bases could effectively prevent excessive tooth reduction in indirect restorations.

With tooth-colored crown restorations, stress distribution is a subject that has been extensively investigated using the finite element method⁶⁻¹²⁾. In the same vein, stress analysis has also been performed on inlay/onlay restorations¹³⁻¹⁶⁾. In essence, these studies primarily discussed the stress generated in the restoratives, and the finite element models in these studies were designed according to the conventional technique, *i.e.*, the entire cavity wall consisted of natural tooth structure without a cavity base. Hence, to the best of our knowledge, no stress analysis has examined indirect restorations in which the entire cavity is prepared in cavity bases.

The purpose of the present study, therefore, was to analyze the stress distribution in indirectly restored teeth of which the restorations were prepared with several cavity bases.

MATERIALS AND METHODS

Determination of elastic modulus and Poisson's ratio
To determine the conditions for finite element stress analysis, the elastic moduli of 18 restorative materials (five ceramics, four restorative resin composites, one core resin composite, three flowable resin

Table 1 Materials used for elastic modulus measurement and their moduli in GPa

Material	Commercial name	Manufacturer	Lot no.	Elastic modulus
Enamel	-	-	-	132 ←
Dentin	-	-	-	40 ←
Ceramic	Ceraeste	Tokuyama Dental, Tokyo, Japan	C050341	155 ←
	OCC	Olympus Optical Co., Tokyo, Japan	98 3005	102
	Finesse	Dentsply Ceramco, Six Terri Lane Burlington, NJ, USA	180399	102
	IPS Empress	Ivoclar Vivadent, Schaan, Liechtenstein	700647	95
	IPS Empress 2	Ivoclar Vivadent, Schaan, Liechtenstein	D61356	145
Restorative resin composite	Herculite XRV (heat)**	SDS/Kerr, Orange, CA, USA	305852	30 ←
	Herculite XRV	SDS/Kerr, Orange, CA, USA	305852	28 ←
	Clearfil AP-X	Kuraray Medical, Tokyo, Japan	510	34
	Filtek P60	3M ESPE, St. Paul, MN, USA	1KL	33
	Clearfil DC Core	Kuraray Medical, Tokyo, Japan	UNI: 0198, CAT: 0120	35 ←
Core resin composite	Revolution Formula 2	SDS/Kerr, Orange, CA, USA	309066	13 ←
Flowable resin composite	Unifil Flow	GC, Tokyo, Japan	310141	19
	Filtek Flow	3M ESPE, St. Paul, MN, USA	3AA	19
Resin composite cement	Nexus 2	SDS/Kerr, Orange, CA, USA	308D62	19 ←
	Bistite II	Tokuyama Dental, Tokyo, Japan	A15434	26
	Panavia F 2.0	Kuraray Medical, Tokyo, Japan	A: 00215A, B: 00121A	24
RMGIC*	Fuji II LC EM	GC, Tokyo, Japan	P: 0202221, L: 0209161	41
Glass ionomer cement	Fuji IX GP	GC, Tokyo, Japan	P: 0301291, L: 0310271	69

*Resin-modified glass ionomer cement. **The composite was cured with light and heat.

Fig. 1 Dimensions of the axisymmetric mesh model for stress analysis. The axiopulpal and axiokingival line angles are rounded ($r = 0.5$). Taper angle of the axial wall is 5 degrees. Load is applied on the cusp tip (triangle).

composites, three resin composite cements, one resin-modified glass ionomer cement, and one glass ionomer cement), human enamel and dentin were measured by nanoindentation technique using a nanoindenter (ENT-1100A, Elionix, Tokyo, Japan)¹⁷⁻¹⁹. Three cylindrical specimens ($\phi 5$ mm $\times$ 4 mm) were prepared for each material and sectioned into halves using a low-speed diamond saw. Sections of the restorative materials were then wet-polished through 1- μ m diamond paste. As for the tooth sections, the crowns of three human molars were sectioned

approximately parallel to the respective occlusal surface, whereby exposed dentin surfaces surrounded by enamel were wet-polished.

Polished sections were subjected to an indentation test. Ten indents were made on each section at a load of 0.005 N. Table 1 lists the measured materials and their elastic moduli, and values indicated by arrows were adopted for stress analysis. As for the Poisson's ratios of the materials, including the tooth substances, they were fixed as 0.3.

Finite element stress analysis

An axisymmetric finite element model was designed for a premolar restored with an onlay (Fig. 1). The mesh model consisted of 7947 nodes and 7842 elements. Dimensions of the model were determined by referencing an artificial tooth (No. B3 DA. 3, Nissin, Kyoto, Japan). Figure 2 shows the six models (Models 1–6) developed using combinations of two onlay materials and three resin composites for the cavity base. The cavity base materials in the six models were as follows—Model 1: no cavity base; Model 2: restorative resin composite; Model 3: core resin composite and a flowable resin composite; Model 4: core resin composite and a flowable resin composite; Model 5: flowable resin composite; and Model 6: flowable resin composite. The difference between Models 3 and 4 was in the area of the two resin composites. As for conditions common among the six models, they were namely: thickness of resin composite cement at 50 μ m; pulp chamber and periodontal tissues were ignored; and the materials, including the tooth substrate, were assumed to be homogeneous, isotropic, linearly elastic, and perfectly bonded^{6,7}.

A vertical load of 95.5 N was applied at three

Fig. 2 Six models designed for stress analysis.

nodes (0.25 mm in width) on the cusp tip at a distance of 2.5 mm from the vertical axis (a large triangle shown in Fig. 1) under the assumption that a total occlusal load of 600 N^{7,9,20)} was applied along the cusp. In an axisymmetric stress analysis, load is generally determined with per radian calculations. Stress analysis was then performed using a finite element analysis software (I-DEAS 10 NX Series m1, UGS Corporation, TX, USA), whereby the distributions and values of tensile stresses among the six models were compared. In addition, the directions of tensile stresses higher than 9.55 MPa under the load of 95.5 N were also evaluated with the models revealing relatively high tensile stresses.

RESULTS

Figure 3 shows the color contours revealed by FEA and the values of tensile stresses. Tensile stresses were generated near the ceramic-cement or resin composite-dentin interface in the six models. In Models 1–3 and 6, tensile stress was recognized at one location, whereas in Models 4 and 5, tensile stresses were recognized at two locations. The locations were as follows: with Models 1–3, it was in ceramic close to the axiopulpal line angle; with Models 4 and 5, it was in ceramic close to the axiopulpal line angle as well as in dentin near the gingival margin; with Model 6, it was in dentin near the gingival margin.

Among Models 1–5 (*i.e.*, ceramic onlay restorations), lowest tensile stress was observed in Model 1, in which the onlay was supported by tooth substances. Tensile stress increased when the tooth substances were replaced with resin composites. Among Models 2–5, the stress in Model 2 was slightly higher

than that in Model 3, and the highest stress value was observed in Model 5 in which the cavity base was flowable resin composite only. In Models 4 and 5, whereby tensile stresses were recognized at two locations, the stress in dentin was lower than that in ceramic.

In Model 6 (*i.e.*, resin composite onlay restoration), tensile stress was observed to be generated in the cervical dentin, but not around the axiopulpal line angle. The tensile stress was slightly higher than that in Model 5, although both cavity base materials were the same.

Directions of stresses were analyzed using Models 5 and 6, whereby the highest tensile stresses were recognized at the ceramic near the axiopulpal line angle and at the cervical dentin, respectively. Arrows in Fig. 4 show the directions of stresses exceeding 9.55 MPa in two locations, with Model 5 on the left and Model 6 on the right. Stress directions in both locations were similar, being parallel to the interface of ceramic-cement or resin composite-dentin.

DISCUSSION

Many previous FEA studies have used elastic moduli measured under diverse and varied conditions. However, the value of elastic modulus is easily affected by measurement conditions. Knowledge of elastic moduli is essential to a FEA study, and the use of moduli measured under the same conditions and with the same method is more appropriate for FEA. In the present study, the elastic moduli used were measured under the same conditions. On this note, results of the present FEA study could be

Fig. 3 Distributions of tensile stresses in the six models. Values given indicate the magnitudes of tensile stress at the load of 95.5 N. Colors closer to red in the color guide bar indicate higher tensile stress values.

Fig. 4 Directions of tensile stresses above 9.55 MPa in Models 5 and 6. Drawings of Model 5 (left) and Model 6 (right) are near the axiopulpal line angle and gingival margin, respectively. Color of arrow ($\leftrightarrow$) closer to red in the color guide bar indicates higher tensile stress value.

considered to be reliable.

Prior to FEA, elastic modulus measurements were performed for 20 materials, including the tooth substances. Out of the 20 moduli, eight were selected for FEA. When a multilayer specimen is loaded, the apparent tensile stresses are generally yielded near the interfaces between the contacting materials and then spread to the material with a higher elastic modulus. Tensile stress increases as the difference between the moduli of the contacting materials becomes larger¹⁰⁾. Based on these considerations, eight moduli were selected in order to simulate severe conditions to reveal the higher tensile stresses.

The Poisson's ratios of the materials were fixed as 0.3, because the ratios of the materials in the present study were estimated to range from 0.2 to 0.4²¹⁾. Moreover, only a slight variation in FEA results are expected if the ratios of the materials vary within this range²²⁾.

Obvious tensile stresses common to the five ceramic restorations (Models 1–5) were found near the internal surfaces of the ceramic onlays. This result agreed with a previous fractographic observation of clinically failed glass-ceramic crowns by Kelly *et al.*²³⁾. They stated that crack initiation sites were located at the internal surfaces of failed crowns. When the ceramic onlay was supported by tooth substances (Model 1), the generated tensile stress was the lowest because the elastic moduli of the tooth substances were higher than those of the resin composite materials evaluated in the present study (Table 1). Among the three resin composites used for the cavity base, the order of elastic moduli was flowable < restorative < core. Therefore, the tensile stress of Model 2 was lower than that of Model 5. Comparing Models 3–5, whereby the cavity base materials were flowable resin composite and/or core resin composite, tensile stress increased as the area of flowable resin composite became larger. In addition, in Models 4 and 5, tensile stress was also generated in the dentin near the flowable composite-dentin interface, whereby the flowable resin composite constituted the majority of the cavity base.

With resin composite onlay restoration (Model 6), distribution of the obvious tensile stresses was different from those in the ceramic restorations. Stress was not observed in the resin composite onlay near the onlay-base interface, because the difference in elastic modulus between the onlay and cavity base was smaller than those in Models 1–5. These findings supported the results of a previous investigation, whereby loads at fracture of all-ceramic crowns were measured when the crowns were supported by resins having different elastic moduli²⁴⁾. It was found that the fracture load of the crown increased markedly with increase in the modulus of the supporting resin.

Maximum tensile stress yielded near the ceramic-cement interface in the ceramic onlay (Model 5) was 18.1 MPa. Peters *et al.*¹⁵⁾ stated that crack initiation started from the internal surface of the ceramic inlay when 55–60% of the load needed for complete fracture was applied to the inlay. Assuming that the tensile strength of dental ceramic was 70 MPa^{11,25)}, 55% of this tensile strength (38.5 MPa) was higher than the maximum tensile stress. Taken together, the ceramic restorative was considered to be resistant to fracture by occlusal loading with the ceramic-cement interface intact. However, when discussing tensile stresses near an adhesive interface, two other major factors should be taken into account: polymerization shrinkage stress of adhesive material^{22,26,27)} and bond strength. Rees and Jacobsen¹⁴⁾ reported that a tensile stress of 6.2 MPa was yielded near a ceramic inlay-cement interface due to shrinkage of cement with a thickness of 100 μm . In the context of the present analysis, the shrinkage stress should be lower because of the smaller thickness (50 μm). Therefore, the assumed total tensile stress was lower than 25 MPa near the ceramic-cement interface. To decrease tensile stress and obtain a better prognosis of a restored tooth, cavity base materials with higher elastic moduli appeared to be more suitable for ceramic restorations.

Tensile stress found near the interface was considered to act as a shear stress at the interface because of stress directions (Fig. 4). However, it would be out of scope and out of context to mention delamination since the present study was performed with an assumption of perfect bonding. On this matter, a three-dimensional finite element contact analysis²⁷⁾ would be aptly competent to discuss about delamination – with reference to interlayer bond strength – between contacting materials.

As for the maximum stress in dentin, 16.2 MPa was generated near the flowable composite-dentin interface (Model 6). Hübsch *et al.*²²⁾ reported that the magnitude of tensile stress reached approximately 5 MPa at the cavity floor of a Class I resin composite filling. Therefore, it might be appropriate to estimate that the maximum tensile stress near the flowable composite-dentin interface was 22 MPa. This stress was also considered to produce an interfacial shear stress, similar to the stress in the ceramic near the ceramic-cement interface.

Comparing resin composites *versus* glass ionomer cements – including resin-modified glass ionomer cements – as cavity base materials, the latter was revealed to have a higher elastic modulus (Table 1). Therefore, if both glass ionomer cement and resin composite were equally efficient in bonding to restorative and tooth, tensile stress yielded by glass ionomer would be lower. However, resin composites generally show higher bond strengths. On this

controversy, Grisanti *et al.*²⁸⁾ stated that the failure loads of human enamel supported by a bonded resin composite, a resin-modified glass ionomer cement, and a conventional glass ionomer cement were not significantly different. The effect of support was presumed to have been enhanced owing to the bonding efficiency. Nonetheless, in terms of comparison verdict, adhesive resin composites with a higher elastic modulus—such as core resin composites—were thought to be more suitable than glass ionomer cements as cavity base materials.

It should be noted that some properties of dental restoratives deteriorate upon exposure to several types of stress in the oral environment. To have a deeper and more thorough understanding of stress distribution in restorations without excessive tooth reduction, subsequent stress analysis should be performed using mechanical data of deteriorated restorations.

CONCLUSION

Based on the results of the present study, the tensile stress generated in the tooth restored indirectly without excessive tooth reduction was concluded to decrease as the elastic modulus of the cavity base material increased.

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