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The Effects of Adhesive Type and Thickness on Stress Distribution in Molars Restored with All-Ceramic Crowns

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Abstract

Purpose: This study investigated the effects of luting cement type and thickness on the stress distribution within all-ceramic crowns using finite element analysis.
Materials and Methods: An all-ceramic crown restoration of the mandibular right first molar was prepared according to standard dental processes and scanned using micro-computed tomography. Eight 3D FE models were then developed that accounted for two adhesive systems, each with cement thickness of 60 μm, 90 μm, 120 μm, and 150 μm. The models were subjected to four loading conditions, and stresses in the veneer and core layers were evaluated.
Results: The stress distribution and maximum stresses in the veneer, core, and cement are presented in corresponding loading conditions. The cement with higher elastic modulus resulted in lower tensile stresses in the veneer and core layers, and the shear strength of the cement was critical to the intactness of the all-ceramic crown.
Conclusion: The cement thickness acts as a cushion between the crown and dentin substrate. Although there is an optimal thickness (approximately 90 μm) that can reduce the stress level in ceramic crowns, cement thickness is not very important to stresses in the core or veneer in most cases when compared to the influence of loading conditions or cement moduli.

Due to ceramics' biocompatibility, mechanical properties (i.e., high-elastic modulus and hardness), and inert qualities, they are widely used in many biomechanical prostheses. For these reasons, ceramics are used in crown replacements, as well as for esthetics. Indeed, there has been gradual transition from the conventional systems comprised of porcelain-fused-to-metal (PFM) core foundations, to all-ceramic crowns. But due to the brittleness of these materials and other related factors, all-ceramic crowns are not as durable as their PFM counterparts, particularly on molars,[1,2] where occlusal loads are large.

Adhesive agents are commonly used to join ceramic crowns to the prepared hard tissue foundation to increase retention,[3] marginal adaptation,[4] and fracture resistance of the restored tooth.[5,6] As such, the effects of adhesives on the mechanical behavior of all-ceramic crowns are of interest for dentists. During the curing process, the resin-luting cements transform from a liquid to solid state. Contraction stresses develop due to corresponding volume and thickness changes, which may affect the longevity of the restored tooth. Alster et al[7] conducted tensile tests with different cement thicknesses and concluded that the contraction stress introduced during curing did not endanger the cohesive strength and that thinner adhesive joints might enhance the clinical success of luted restorations. In contrast, using experimental and theoretical methods, Choi and Condon[8] found that the contraction stress decreased significantly as the adhesive thickness increased from 20 to 300 μm. Ausiell et al[9] and Al-Makramani et al[10] discussed the contribution of compliant and rigid adhesives as well as the corresponding cement thickness to stresses. Due to complex crown geometry and its multiple layered structures, a direct experimental evaluation on the effects of adhesive thickness to stresses and the failure resistance of real restored teeth has not been reported.[11] Thus, there is presently no clear recommendation for the adhesive thickness that should be used for all-ceramic crowns to minimize deleterious stresses at the bonded interface and in the crown, as well as to optimize long-term performance. Past research has been conducted assuming the thickness varied from 25 to 140 μm.[12-14] A finite element analysis (FEA) can serve as an effective method to evaluate the importance of adhesive thickness and adhesive constitutive behavior on the stress distribution that develops under oral function.

In this study, FEA was adopted to determine the stress distribution in all-ceramic restorations (IPS e.max Press; Ivoclar Vivadent, Schaan, Liechtenstein) cemented by two adhesive agents with four thicknesses. The 3D model was constructed from a standard ceramic crown restoration prepared for a mandibular right first molar. Four loading conditions were considered. The maximum tensile stresses in the veneer and core layers were determined, and their relationships to the adhesive thickness were identified. The maximum tensile stress and shear stress in the cement were also analyzed.

Table 1 FE model meshing details

Cement type	Cement thickness	Elements	Nodes
Panavia F	60 μm	676,393	967,891
	90 μm	671,284	955,507
	120 μm	693,850	970,159
	150 μm	576,618	839,187
Variolink II	60 μm	569,948	821,406
	90 μm	616,224	881,197
	120 μm	592,936	848,800
	150 μm	587,193	845,406

Materials and methods

Preparation of the dummy restored crown

The dental ceramic crown used in this investigation was IPS e.max Press (Ivoclar Vivadent). A plaster mold and a concave silicon rubber mold were duplicated from the standard Asian first right mandibular molar (D50-500A, Nissin Dental Products Co., Ltd., Kyoto, Japan). The crown of the duplicate was trimmed so that the occlusal reduction was about 2 mm at the contact area, with coronal length of 4 mm; the shoulder was prepared with 1 mm reduction on the lingual and buccal surfaces. The trimmed tooth was tapered at 8° with a 1 mm shoulder of 90°. Then, the trimmed plaster mold was used to duplicate the dental substrate with Z100 restorative polymer (3M ESPE, St. Paul, MN). Instead of manufacturing the crown using IPS e.max Press with the hot press procedure, the core and veneer were made with a unique mixture of barium sulfate and denture base resin (Type II, Shanghai Medical Instruments Co., Ltd., Shanghai, China) to develop different grayscale levels under X-ray radiation. The ratios of these two components are 3:10 and 1:10 for the core and veneer, respectively.

After the mixture of powder (3:10 ratio) was placed in the facet area of the concave silicon rubber mold, the trimmed dental substrate was pressed into the rubber mold and hardened. After a careful sanding and polishing process, the core layer was formed with a 0.8 mm thickness. Then the core was adhesively bonded to the dental substrate. Note that the luting process is usually carried out to close the dentin tubules and enhances the bonding strength to the tooth substrate. Furthermore, a preconditioning process such as application of a silica coating is often used to achieve higher bonding strength, especially in zirconium or alumina ceramics.[15,16] These steps were ignored during preparation of the dummy restored ceramic crowns, as they would not influence the FE models. The mixture of powder (1:10 ratio) was placed in the rubber mold following the same procedure in which the veneer was built on the top of the core. The average thickness of the facet area of the total core and veneer was 2 mm, and the thickness of core and veneer gradually decreased to 1 mm at the shoulder.

Generation of the numerical models

The restored tooth was scanned with a General Electric Company micro-computed tomography (CT) scanner with 20 μm voxel resolution. The sequential sliced images were imported into commercial 3D image conversion software (Simpleware Version 3.1, Exeter, UK) in Dicom format.[17] There are three modules in Simpleware (ScanIP, ScanFE, and ScanCAD). ScanIP converts the sliced images acquired from CT or magnetic resonance imaging (MRI) into a numerical 3D model, and ScanFE provides a mean for smoothing the surface, assigning material properties and meshing. The output file was imported into ANSYS (Version 11.0, Canonsburg, PA) for FEA. Since the thickness of the cement layer was about 5 pixels, manual boundary segmentation at the interface of the core and the tooth substrate was carried out in each sliced image. By diluting the boundary line of the tooth substrate, four 3D restored tooth models with different cement thicknesses (60 μm, 90 μm, 120 μm, and 150 μm) were constructed. Two types of cements (Panavia F and Variolink II) were considered as the adhesive agents. Thus, eight numerical models were generated in total, including two types of adhesive resin cements and four thicknesses. Details of the final meshed models are listed in Table 1. As the eight FE models had different numbers of elements and nodes, quantitative differences in the stress values among these models were of concern. Thus, a convergence analysis was conducted. As an example, the FE model (cement: Variolink II, thickness: 90 μm, loading Condition: III) was meshed with 532,052, 616,224, and 703,969 elements, respectively. The stress distribution resulting from the three mesh densities were identical. The maximum principal stress in each layer (Table 2) is consistent despite the increase of mesh density, thereby indicating sufficient density was achieved. Note that there were only 2302 elements in Imanishi et al's[18] all-ceramic crown model and 50k to 65k elements in De Jager et al's model.[19] The numerical mesh presented in this study has sufficient density to ensure accuracy of the stress analysis.

Assumption and boundary conditions

The bottom of each restored tooth model was constrained by making all displacements equal to zero. Effects of the periodontal ligament to the crown were neglected[12] since the main load was applied along the tooth axis, and only the stress magnitude was analyzed. As for the intact dental crown, the veneer layer was tied to the core. Similarly, the inner core and tooth substrate surfaces are bonded with the cement; as such, the elements at these interfaces were assumed to be tied so the deformed displacement was continuous across the interface. Once the internal stress exceeds the strength of the materials, failure can occur in the corresponding materials or interfaces.

Table 2 Examination of convergence of the FE models

	Principal stress (MPa)					
	Veneer		Core		Cement	
Element number	Upper surface	Lower surface	Upper surface	Lower surface	Tensile	Sheer
532,052	70.312	33.068	40.581	94.836	10.071	18.393
616,224	70.312	33.071	40.578	94.838	10.074	18.390
703,969	70.309	33.070	40.582	94.835	10.076	18.392

The mechanical properties of materials involved in the numerical simulation are listed in Table 3 and are from various sources.[17,20–24] The ceramic crown layers and the luting cements were assumed to be homogeneous, linearly elastic, and isotropic. Though from a microscopic view, dentin is structurally anisotropic, it is essentially mechanically isotropic.[25] Thus, the dentin was assumed to behave as a homogeneous, linearly elastic, and isotropic material. Although there are many kinds of adhesive resin cements used for bonding crown restorations, only Panavia F and Variolink II were selected, as Young's modulus of Variolink II is roughly two times larger than that of Panavia F. The mechanical effects of these two cements were compared by considering the difference in the material properties.

The contraction stress of resin cements resulting from the curing process has been considered important to the mechanical behavior of all-ceramic crowns. Choi and Condon[8] indicated that such influence is inversely proportional to the cement thickness; for a thickness of 60 to 150 μm, the magnitude of the contraction stress is below 10 MPa. Similarly, De Jager et al[19] reported that the tensile stress due to cement shrinkage was comparatively small for ceramic crowns. Consequently, contraction stress in the cement was neglected.

Loading conditions

Four occlusal loading conditions were considered. In Condition I (Fig 1A), the occlusal load was applied at the wear facets, including three points each on the inner and outer inclines of the buccal cusps, and three and two points on the inner inclines of the lingual cusps (eight points total). A total load of 600 N, 75 N for each loading point, was applied along the tooth axis.[18] In Condition II, the masticatory load was applied at three points on the outer inclines of the buccal cusps. Since typical masticatory forces are about 37%[26] to 40%[27] of maximum bite force, a total load of 225 N was applied at an angle of 45° to the tooth axis (75 N at each loading point) (Fig 1B). In Condition III, a concentrated occlusal load was applied at the central fossa region (Fig 1C). To simulate the actual contact condition with the opposite tooth cusp having a 3-mm radius, the loading zones were two small regions near the central fossa.[28] The resultant load was 600 N with direction aligned vertically along the tooth axis. The last loading condition has the same contact zones as Condition III, but the resultant occlusal load (600 N) was 10° inclined with the tooth axis in the lingual-buccal plane (Fig 1D).

Table 3 Material properties used in the models

Materials	Young's modulus (MPa)	Poisson's ratio
Veneer	70,000	0.24
Core	91,000	0.23
Panavia F	4040	0.35
Variolink II	8300	0.35
Dentin	18,600	0.31

Results

To show the stress distribution inside the restored crown, a lingual-buccal section across the central fossa was selected (Fig 2). The maximum tensile stress occurs at the outer surface of the veneer and lower surface of the core. It was found that the stress distribution largely depends on the loading conditions. An example of a 3D view of the stress distributions within the veneer, core, and resin cement layers is shown in Figure 3. In this figure, the all-ceramic crown was modeled with a cement thickness of 90 μm and subjected to a concentrated load of 600 N (Condition IV). The numerical results indicate that neither the cement material properties nor the cement thickness are important to the overall internal stress distribution of the all-ceramic crown when subjected to the same loading condition; however, the magnitude of maximum principal stress in each layer indeed changes with the cement type and thickness. Due to its potential importance in crown failures, the maximum principal stresses at each interface of the ceramic crowns with each cement and loading condition are presented in Table 4. The maximum principal stresses at the upper surface of the veneer were quantified by averaging ten values at a distance of 2 mm surrounding the loading center. The maximum tensile stresses were found at the upper surface of the veneer and lower surface of the core in each loading condition (Table 4).

Discussion

For brittle materials like ceramics, tensile stress is more likely than compressive stress to cause material failure. As evident from the maximum stresses resulting from the four loading conditions (Table 4), the concentrated load at the central fossa (Conditions III and IV) caused severe tensile stress in the crown. In comparison, the more distributed bite and masticatory loads

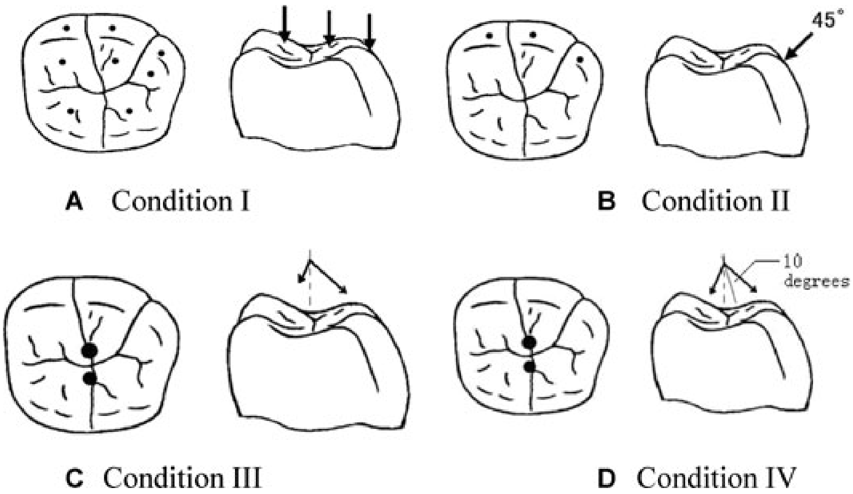

Figure 1 Loading conditions of the all-ceramic crown. (In Conditions I, III, and IV, a total of 600 N bite force was applied, while in Condition II, 255 N masticatory force was applied.) (A) Condition I, (B) Condition II, (C) Condition III, and (D) Condition IV.

(Conditions I and II) are much less detrimental to the restored crown. This suggests that the occlusal facets of the restored crown should be shaped according to the profile of the opposite tooth to minimize concentrated contact at a single point during function. A sharp load on top of the crown could potentially cause damage to the crown restoration.[29] As partly evident in Figures 2 and 3, it was also found that the off-axis load (Condition IV) could cause larger tensile stress, especially in the shoulder areas at the buccal and lingual sides. Regardless of the loading condition, one can find that the maximum tensile stress exists at the upper surface of the veneer and lower surface of the core.

Adhesives join the ceramic crown to the tooth foundation. Because they are relatively soft and compliant (i.e., low-elastic modulus), adhesives distribute the stress from one layer to the next with minimal resistance, which facilitates development of a large flexural stress in the upper layer of the crown. From a mechanical point of view, cured Panavia F is more compliant than cured Variolink II. Table 4 reveals that a cement with lower elastic modulus could cause larger tensile stress both in

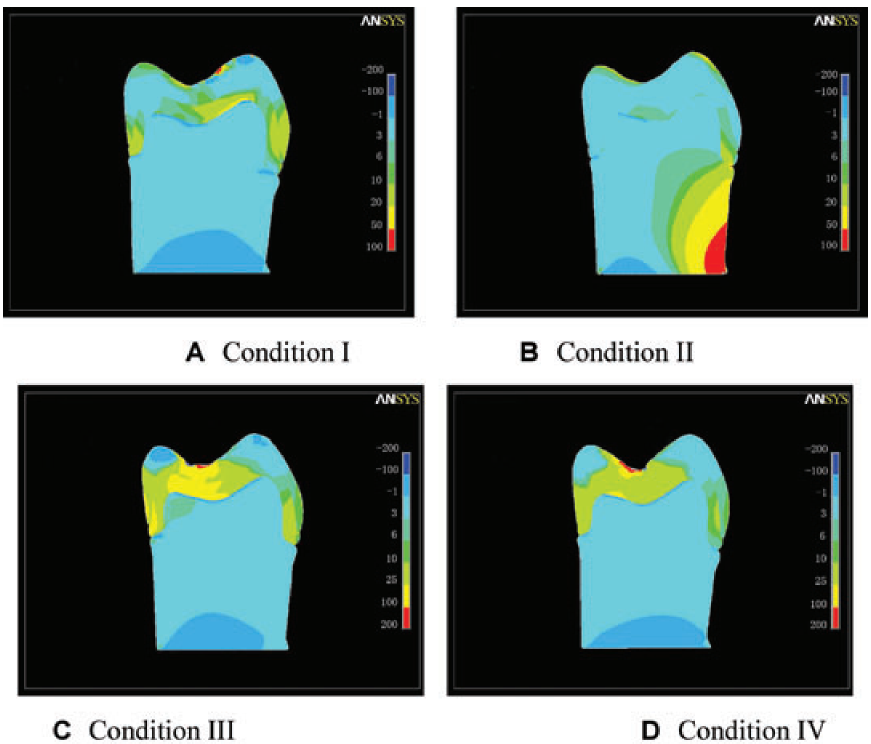

Figure 2 Stress distribution at the lingual-buccal section across the central fossa. (A) Condition I, (B) Condition II, (C) Condition III, and (D) Condition IV.

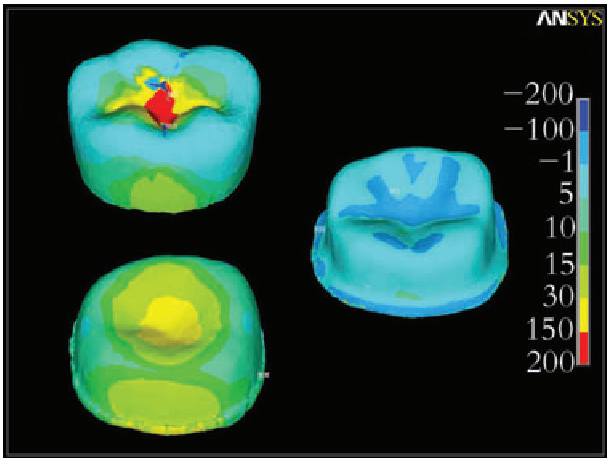

Figure 3 Stress distribution in the veneer, core, and cement when the crown is subjected to loading Condition IV.

the upper surface of the veneer and in the lower surface of the core due to the aforementioned mechanism. Conversely, the more rigid cement could effectively reduce tensile stresses in the upper veneer surface and in the lower surface of the core. As an example, in the case of a cement thickness of 150 μm for Condition III (Table 4), one can find that the maximum tensile stresses were approximately 78 MPa in the veneer surface and 119 MPa in the core for Panavia F, while the maximum tensile stresses were 73 MPa in the veneer surface and 106 MPa in the core for Variolink II. This causes about 6% and 10% variation of stress in both veneer and core, respectively, which is attributed to cement modulus. With the recent development of glass-infiltrated zirconia and alumina ceramic core materials with higher flexural strength, the maximum flexural stress may not be a primary concern for dentists. Resin cements provide adhesive strength to the ceramics with proper conditioning processes.[15,16] Yet the use of more rigid adhesives can result in a reduction of stress in the veneer to some extent. In this regard, Variolink II appears to be more suitable for all-ceramic crown restorations.

Table 4 Maximum principal stress in the crown layers resulting from the different cement type, cement thickness, and loading conditions

Cement type	Layer	Site	Cement thickness (μm)	Load condition (MPa) I	II	III	IV
Panavia F	Veneer	Upper surface	60	23.54	19.45	74.09	72.85
			90	23.13	19.00	73.58	71.29
			120	24.05	19.27	74.63	73.68
			150	24.97	20.03	77.86	75.13
		Lower surface	60	7.33	7.67	35.83	34.28
			90	7.22	7.30	35.22	33.31
			120	7.44	7.36	35.89	35.32
			150	7.92	7.95	39.48	38.51
	Core	Upper surface	60	12.27	10.01	44.96	43.28
			90	11.20	9.54	42.67	41.66
			120	12.55	9.66	44.01	43.44
			150	12.96	10.40	47.63	47.45
		Lower surface	60	28.30	13.57	105.35	94.34
			90	31.10	12.17	106.10	94.41
			120	33.01	13.35	107.92	98.93
			150	33.55	14.69	118.52	107.02
Variolink II	Veneer	Upper surface	60	23.07	19.53	72.58	70.19
			90	22.69	18.84	70.31	68.20
			120	23.33	19.65	71.86	70.86
			150	23.99	19.90	73.25	72.27
		Lower surface	60	7.01	7.72	37.97	35.87
			90	6.99	7.35	33.07	32.35
			120	7.01	7.50	35.07	34.16
			150	7.32	7.88	38.07	35.39
	Core	Upper surface	60	11.79	10.12	45.96	44.85
			90	11.60	9.85	40.58	40.56
			120	12.13	9.64	42.87	42.75
			150	12.70	10.34	46.14	43.88
		Lower surface	60	29.42	13.53	99.59	89.21
			90	27.26	12.06	94.84	86.12
			120	27.73	12.76	97.79	89.04
			150	28.80	13.89	106.21	94.27

Table 5 Maximum stresses in the cement layers resulting from the different cement type and cement thickness

Cement type	Stresses	Cement thickness (μm)	Load condition (MPa)			
			I	II	III	IV
Panavia F	Maximum principal stress	60	6.82	6.40	15.30	10.72
		90	6.19	5.58	10.03	7.09
		120	6.21	6.01	10.20	7.49
		150	7.91	7.21	12.24	8.78
	Maximum shear stress	60	7.73	7.01	18.83	17.87
		90	6.63	6.70	15.03	15.24
		120	6.65	6.51	14.80	14.69
		150	6.52	7.44	15.10	15.52
Variolink II	Maximum principal stress	60	6.95	6.32	13.13	9.55
		90	5.86	5.82	10.07	7.35
		120	5.86	5.97	10.51	7.78
		150	7.83	7.03	12.54	9.03
	Maximum shear stress	60	8.24	7.98	21.28	20.37
		90	7.63	7.57	18.39	18.13
		120	7.65	6.97	18.04	17.56
		150	7.57	7.28	18.69	17.85

To maintain intactness of a restored crown without debonding failure,[28] it is important to control stresses in the cement. Consequently, the stresses resulting from use of the two dental adhesives were estimated. Based on earlier reports,[15,30-60] the tensile strength for Panavia F and Variolink II is 19.4 ± 11.2 MPa and 19.4 ± 14.6 MPa, respectively. Similarly, the shear strength for these materials is 14.7 ± 6.8 MPa and 17.78 ± 9.9 MPa, respectively. Note that these values were estimated by averaging the strength obtained in individual studies and reported in the literature. The large standard deviation in these quantities indicates that the tensile and shear strength of the cement agents may vary over a relatively large range depending on the service conditions. The maximum tensile stresses resulting from the four loading conditions for the two cements listed in Table 5

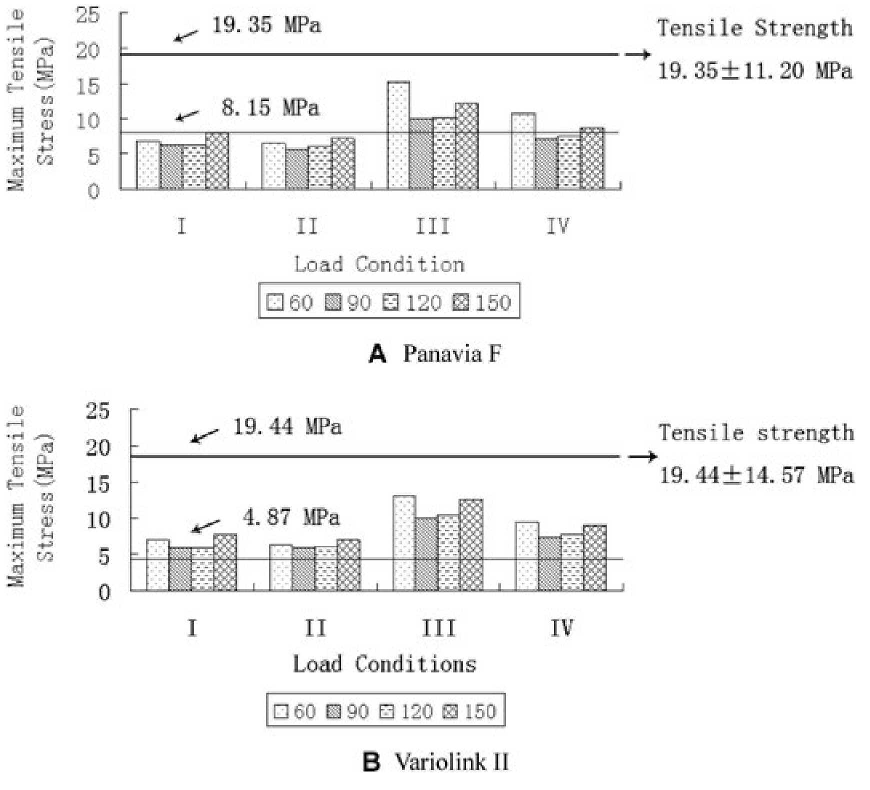

Figure 4 Maximum tensile stress in the cement. (A) Panavia F and (B) Variolink II.

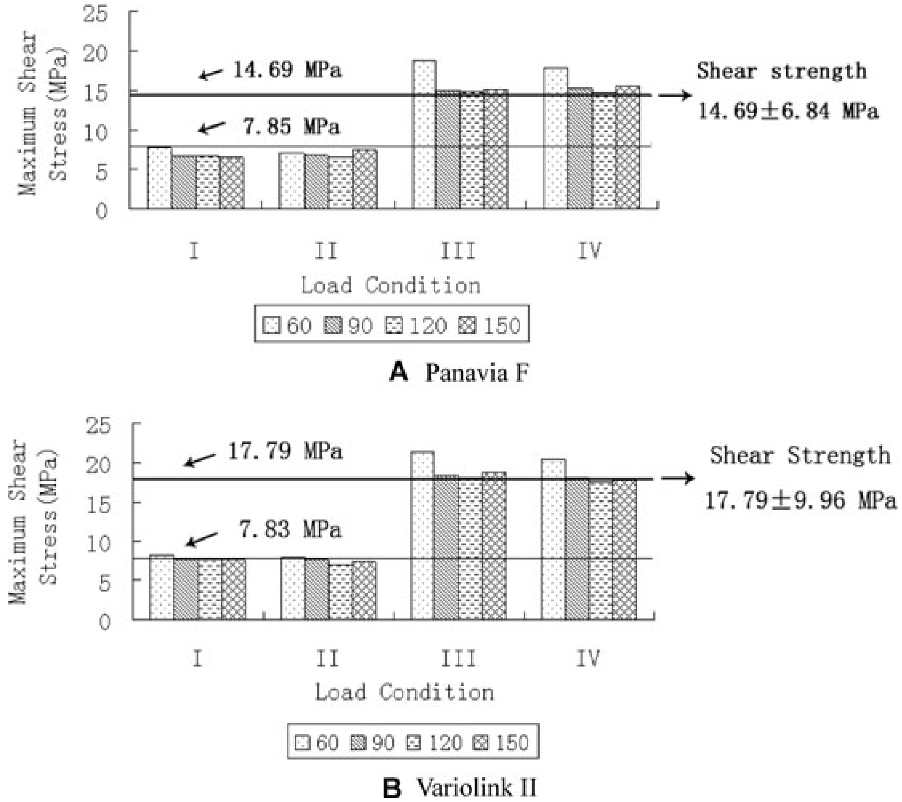

Figure 5 Maximum shear stress in the cement. (A) Panavia F and (B) Variolink II.

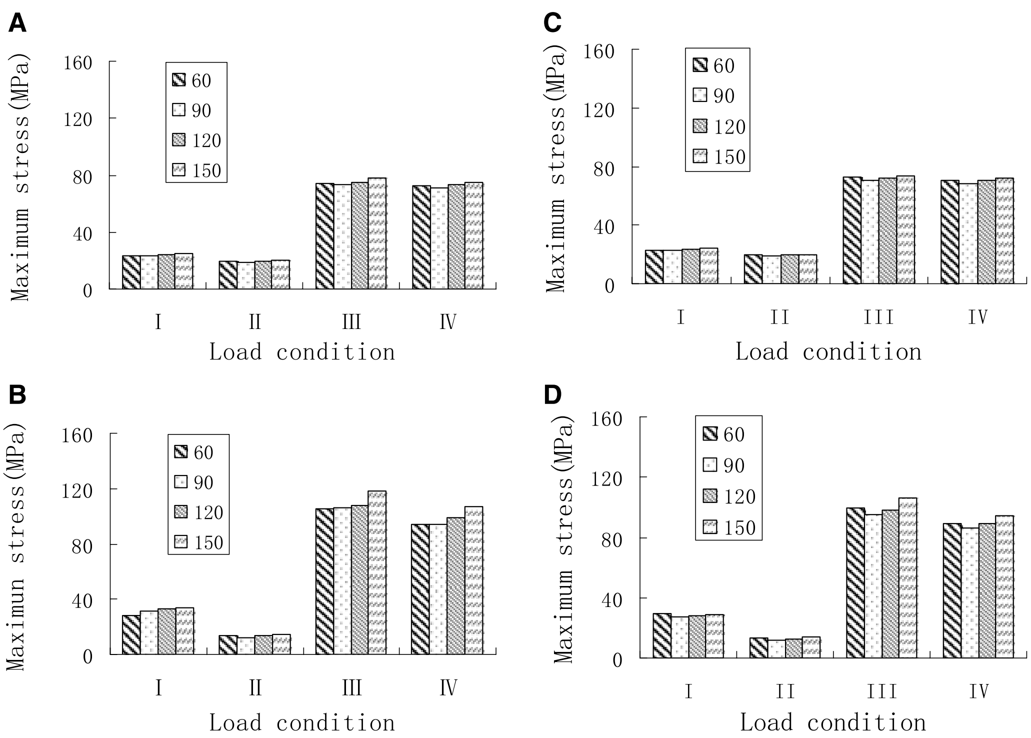

Figure 6 Comparisons of the maximum principal stress with the cement thickness (in μm) in the four loading conditions. (A) Stress at the upper surface of the veneer, Panavia F; (B) Stress at the lower surface of the core, Panavia F; (C) Stress at the upper surface of the veneer, Variolink II; (D) Stress at the lower surface of the core, Variolink II.

are compared to the strength in Figure 4 using the maximum normal stress criteria. Only the average tensile strength and minimum tensile strength are displayed to simplify the comparison. As evident from Figure 4, none of the four loading conditions would cause failure of the two cements, as the tensile stresses are all below the average strength. The maximum shear stresses resulting from the four loading conditions for the two cements listed in Table 5 are also compared to the shear strength using the maximum shear stress criteria in Figure 5. Notably, the shear stresses resulting from loading conditions, III and IV, exceeded the average shear strength of the cements. These two conditions could cause failure inside the cement and eventually cause debonding. Methods employed to improve the shear strength of the adhesives or to lower the shear stress in the bonding zone would be needed to maintain the intactness of the all-ceramic crown.

Due to inappropriate preparation of the tooth and errors in manufacturing the ceramic crown, the gap between the tooth substrate and crown is often different from that desired. The extra space is filled with additional resin adhesives. One could find crown cement thickness varying from 20 to 200 μm.[11] According to reported findings,[7,61] tensile joint strength varies inversely with the layer thickness. As a result, to minimize the disadvantages of this weak link, dentists have strived to produce a cement layer as thin as possible. But it is important to emphasize that the adhesive thickness influences the magnitude of stress in the crown layers as well. The maximum tensile stresses at the veneer and core surfaces are presented for cement types and thicknesses under the four loading conditions in Figure 6. Interestingly, for many of the cases considered, when the cement thickness reaches 90 μm, the maximum stresses in the core and in the veneer reach the minimum. A maximum of 5% reduction of stress in the core and veneer occurs with increasing thickness from 60 to 90 μm in loading Condition III. Similarly, the stress level increases by 10% when the thickness reaches 150 μm. From a mechanical perspective, the cement also acts as a compliant foundation between the ceramic crown and dentin substrate. Thus, a large cement thickness enables a larger degree of flexure of the crown, and a corresponding larger tensile stress develops in the core (Fig 6B and D). Conversely, if the cement thickness is very thin, the ceramic crown will be very close to the dentin substrate, which is a stiffer material. In this condition, the thin cement layer cannot fully absorb the mechanical energy through deformation, which causes an increase of stress in the crown. These findings agree with those of Brukl and Philp.[62] Owing to these two different aspects of behavior, the results suggest there is an optimal cement thickness around 90 μm for minimizing the stress in the restored crown; however, compared to the influence of loading condition, it is not a very important factor for maintaining the intactness of an all-ceramic crown. Under severe loading conditions, the shear stress in the cement would cause debonding, which eventually leads to failure of the restored crown.

Conclusion

A 3D numerical analysis was conducted to study the influence of cement type and cement thickness on the mechanical behavior of all-ceramic crowns. Specifically, eight FE models were developed including two luting cements (Panavia F and Variolink II) and four cement thicknesses (60 μm, 90 μm, 120 μm, and 150 μm). The cement with larger elastic modulus resulted in lower tensile stresses in the veneer and core layers. Also, in predictions of cement failure by tensile or shear stresses, it was shown that the shear strength of the cement is critical to maintaining the intactness of all-ceramic crowns. Results of the numerical simulations also indicated there is an optimal thickness (approximately 90 μm) that can reduce the stress level in all-ceramic crowns; however, the cement thickness is of secondary importance to stresses in the core or veneer when compared to the influence of loading conditions or cement moduli.

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