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Stress relieving behaviour of flowable composite liners: A finite element analysis

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The purpose of this study was to investigate the consequences of using flowable composite as a liner beneath class I resin composite restorations on polymerization shrinkage stress and occlusal force. Models of class I resin composite restorations were generated. A control model received no flowable composite liner. Thirteen test models received different flowable composite liners with varying elastic modulus. Finite element analysis was used. The polymerization shrinkage of the resin composite and an occlusal force were simulated in the models. The stress and strain energy density in each model were investigated. The results demonstrated that all flowable composite linings were able to reduce polymerization shrinkage stress and occlusal force in enamel, dentin, the hybrid layer, and the adhesive layer to various degrees in tooth-restoration systems. Therefore, additional techniques may be applied to reduce the remaining stress and to ensure the long-term success of restorations.

Keywords: Elastic cavity wall, Flowable composite, Elastic modulus, Polymerization shrinkage, Strain energy density

INTRODUCTION

The increasing demand for esthetic dentistry has encouraged the use of resin composites for restoring anterior and posterior teeth. However, creating a successful resin composite restoration is still a complex task especially in posterior teeth. The main problems with direct posterior resin composite restorations are excessive wear, postoperative sensitivity, open contact area, and recurrent caries[1)]. As a result of polymerization, the bulk of resin composite shrinks approximately 2.0 to 5.6% by volume immediately after being light-cured[2)]. During the bonding and polymerization of resin composites, two forces act simultaneously on the tooth/restoration interface: the bonding force and the shrinkage force, respectively[3,4)]. The competition between these forces creates stress in the tooth/restoration interface and causes tooth deformation[3-5)]. The magnitude of the stress generated from polymerization is related to the configuration factor (C-factor)[6)], the viscoelastic properties of the resin composite[7)], and the compliance of the bonded substrate[6,7)].

In most restorations in posterior teeth, the C-factor is greater than 1. This is particularly so in class I and class V restorations where the C-factor is 5[8)]. When the resin composite bonds to such a cavity, volumetric shrinkage creates stress in both the material and the surrounding tooth structure. If compliance of the bonded substrate is insufficient, disruption of the bonded interface or fracture of the tooth structure may occur[4)].

The method of lining the cavity wall with low elastic modulus materials, known as the elastic cavity wall concept, has recently been used to relieve shrinkage stress in clinical situations[9)]. The intermediary layer of the liner acts as a stress-absorbing layer, hence, reducing the stress transmitted to the toot[9-11)]. Van Meerbeek and co-workers reported that the interdiffusion zone and adhesive resin were less rigid than the normal dentine[12)]. Furthermore, the combination of a low elastic modulus hybrid layer and a thick adhesive layer could create an artificial elastic cavity wall[13)].

Since its first introduction in the market in 1996, flowable composites have become popular more for their special handling characteristics than for their clinical performance[14)]. To maintain the flow of the material, the composite needs a high percentage of diluent resin monomers, such as TEGDMA, and a low filler load. Hence, the flowable composite's elastic modulus is lower than the one from the regular restorative resin composite[2)]. Condon and Ferracane explained that reducing filler load results in more shrinkage, less stress and a lower tensile modulus[15)]. This characteristic is useful for creating the elastic cavity wall. Several authors have successfully demonstrated the use of a flowable composite as an intermediary layer[10-12)]. However, the results are inconsistent due to the variety of materials and the adhesive system used in the study[11)].

The question remains concerning how low the elastic modulus should be for the flowable composite to become an excellent stress absorber. Finite element analysis (FEA) has recently been used to explain some of the dilemmas in dental materials regarding stress and strain. This analysis involves a program that analyses information of elastic moduli and Poisson's ratios of different biomaterials and subsequently calculates the resulting stress and strain generated. The objective of this study was to use FEA to determine the suitable elastic modulus of flowable composites used as the intermediary layer.

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MATERIALS AND METHODS

Creating a tooth-restoration model for analysis

Utilizing imaging software (Unigraphic NX 2.0, Electronic Data Systems Corporations, Texas, USA), we were able to create a 2-dimensional class I tooth-restoration model for the analysis. The model consisted of enamel, dentine and a resin composite restoration.

All the components were assembled into a magnified class I occlusal restoration as depicted in Fig. 1.

The dentin-enamel junction was assigned to be at 1.5 mm below the outer surface, according to the dental literature. The class I cavity was made in the form of a rounded rectangular shape. The cavity was created using the deepest part of the occlusal surface as the reference point, 2 mm deep and 2 mm wide (1 mm apart from the reference point). The class I resin composite restoration in dentin was surrounded by 3 layers of different materials: a layer of flowable composite (assigned thickness=500 μm), a layer of adhesive resin (assigned thickness=10 μm) and a hybrid layer (assigned thickness=5 μm). Therefore, there were only 2 layers of flowable composite and adhesive resin (without hybrid layer) in the enamel.

The thickness of the hybrid layer was based on the work of De Munck *et al.*[16] and Pashley *et al.*[17]. The thickness of the flowable composite layer and the adhesive layer was based on the work of Unterbrink and Liebenberg[10]. The order of layers is illustrated in Fig. 1.

Assigned material properties

The tooth model was then imported to the FEA software (ABAQUS 6.0). For calculation of the FEA, the Poisson's ratio and the elastic modulus of all materials were entered (Table 1). All materials were assumed to be isotropic and linearly elastic.

Assigned element types and meshing parts

Element types were linear, triangular, and quadrilateral. There were 453,487 triangular elements successfully meshed in the enamel, dentin, and resin composite. In the minute structure of the hybrid layer and the adhesive layer, a quadrilateral element type was chosen as a pattern of the stress result. There were 17,745 of quadrilateral elements in the hybrid layer and the adhesive layer.

Effect of polymerization shrinkage

Polymerization shrinkage of the resin composite was based on the distance of cuspal deflection, which was found to be 16 μm for Z250 in premolars[18]. The simulation was performed by setting the temperature shrinkage value[19]. We found that if the temperature was decreased 1 degree, the deflection would be 8 μm in average on all sides of the cavity. Therefore, we set the primary temperature at 25° and then decreased it to 24° to create the shrinkage force.

Effect of occlusal force

Immediately after polymerization shrinkage, the model was subjected to an occlusal load of 50 N[20,21]. The load was applied at the reference point on the occlusal surface, parallel to the long axis (Fig. 1).

Data analysis

1. Percentage difference of Von Mises stress and total strain energy density

The Von Mises stress (MPa) and total strain energy density (MPa/1,000) from each structure were obtained from all models. The control model (without any flowable composite lining) showed the maximum Von Mises stress and maximum total strain energy density. The control model was compared to the test models to determine the effect of the flowable composite liner.

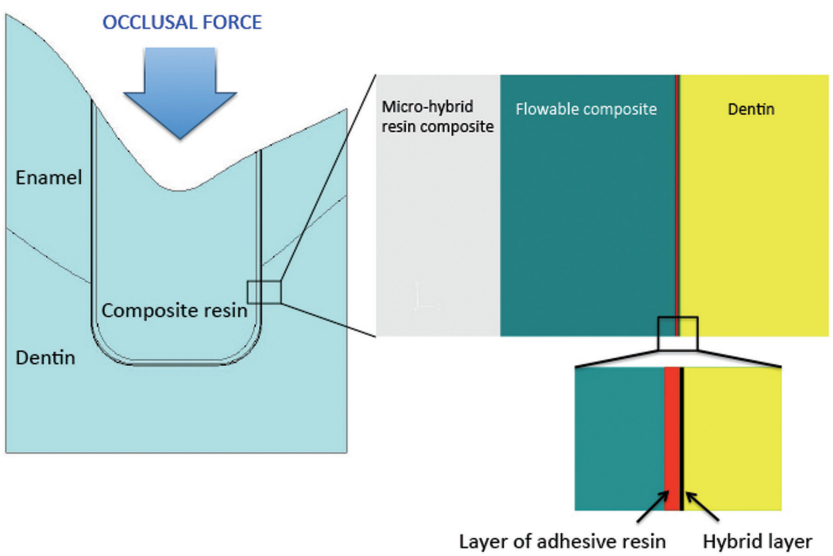


Fig. 1 Model assembly used in the analysis.

Table 1 Elastic modulus and Poisson's ratio of enamel, dentin, hybrid layer, adhesive resin, flowable composites and composite resin

Materials	Elastic modulus (MPa)	Poisson's ratio	Reference
Enamel	87,500	0.25	Habelitz *et al.*, 2001
Dentine	25,111	0.30	
Hybrid layer of adhesive resin: Single bond 2 (3M ESPE, St Paul, MN, USA)	11,765	0.31	Pongprueksa *et al.*, 2008
Adhesive resin: Single bond 2 (3M ESPE)	8,430	0.31	
Flowable composites:			
Durafill Flow (Heraeus Kulzer, Wehrheim, Germany)	6,499	0.31	Labella *et al.*, 1999
Aeliteflo LV (Bisco, Schaumburg, IL, USA)	6,861	0.31	
Glaze (Bisco)	7,384	0.31	
Aeliteflo (Bisco)	7,410	0.31	
Revolution (Kerr, Orange, CA, USA)	7,713	0.31	
Starflow (Danville Materials, San Ramon, CA, USA)	7,922	0.31	
Florestore (Dent-Mat, Santa Maria, CA, USA)	8,113	0.31	
Ultraseal XT plus (Ultradent Products, South Jordan, UT, USA)	8,642	0.31	
Versaflow (Centrix, Shelton, CT, USA)	10,737	0.31	
Snowwhite B (Coltene/Whaledent, Altstatten, Switzerland)	10,891	0.31	
Crystalessence (Confi-Dental Products, Louisville, CO, USA)	10,961	0.31	
Tetricflow (Vivadent, Schaan, Liechtenstein)	11,530	0.31	
Permaflo plus (Ultradent Products)	12,484	0.31	
Composite resin: Z250 (3M ESPE)	24,494	0.31	Pongprueksa *et al.*, 2008

This result was important because polymerization shrinkage can be responsible for the immediate failure of resin composite restorations. On the other hand, strain impacted the durability of the restoration because it made the material more vulnerable to fatigue failure.

2. Linear equation

The maximum Von Mises stress in each structure was calculated with a linear equation. This equation allowed us to estimate the most suitable elastic modulus of flowable composites for relieving the stress caused by polymerization shrinkage and occlusal force.

RESULTS

Effect of polymerization shrinkage

The maximum stress found in a controlled model (62.75 MPa) was located in the enamel at the cavosurface margin without a flowable composite lining (Fig. 2A). A sample of stress pattern in a cavity model with Aeliteflo as the lining material is shown in Fig. 2B. The maximum stress (40.88 MPa) was located in the enamel at the cavosurface margin.

The maximum Von Mises stress values due to polymerization shrinkage and the percentage differences between test and control models for each substrate are demonstrated in Table 2. The maximum stress in all models was located in the enamel at the cavosurface margin.

For enamel, the maximum stress of the control model was 62.75 MPa. For the test models, the maximum stresses were reduced to 39.79–44.56 MPa in relation to the elastic modulus of the flowable composites. Flowable composite linings were able to reduce the maximum stress on enamel to varying degrees. The amount of stress reduction varied according to the elastic modulus of the liner. The results showed that the flowable composite lining could reduce stress on the enamel by 28.99 to 36.59%. The greatest stress reduction was found in the model with Durafill Flow lining.

For the dentine, polymerization shrinkage created stress that was most concentrated at the angle of the cavity. Maximum stress of 20.17 MPa was found in the control model. With the test models, the maximum stresses were reduced to 16.22–16.94 MPa with a range from 19.58 to 16.01% compared with the control.

The hybrid layer is the thinnest structure in the model (5 μm), which was affected by polymerization shrinkage. Stress reduction was found at hybrid layer in all models with the application of the flowable composite. The stress reducing capability of the flowable composite liners was related to the elastic modulus of the material. The lining was able to decrease the stress in the hybrid layer from 15.07 to 19.83%.

The adhesive layer also presented stress due to the polymerization shrinkage of resin composite. Stress was

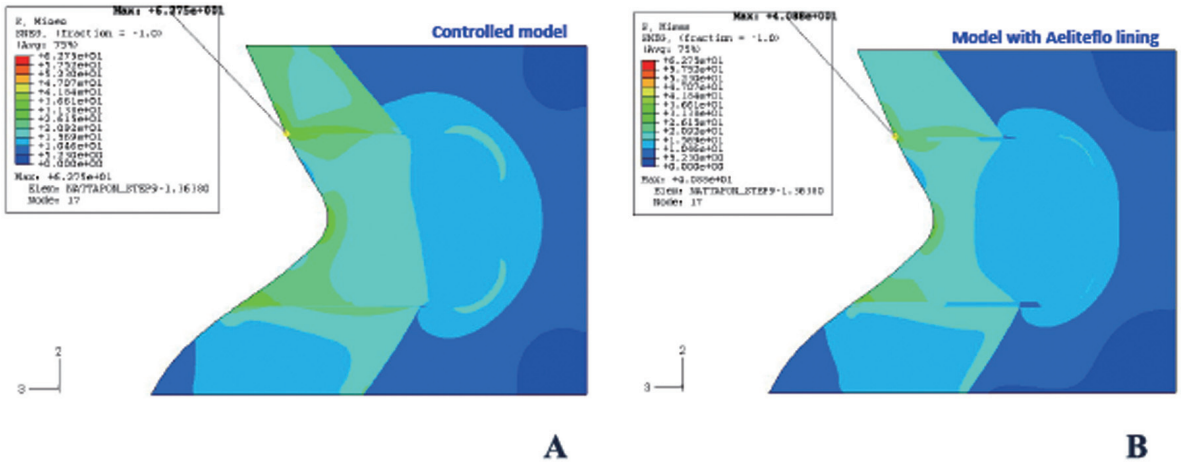


Fig. 2 Von Mises stress pattern due to polymerization shrinkage in the control model (A) and the model lined with flowable composite (B).

Table 2 Maximum Von Mises stresses (MPa) by the effect of polymerization shrinkage and percentage differences from control groups in each substrate

Materials	Enamel		Dentine		Hybrid layer		Adhesive layer		Composite	
	Stress	Percentage different	Stress	Percentage different	Stress	Percentage different	Stress	Percentage different	Stress	Percentage different
Control	62.75	0.00	20.17	0.00	16.19	0.00	54.63	0.00	42.11	0.00
Durafill flow	39.79	−36.59	16.22	−19.58	12.98	−19.83	35.26	−35.46	35.26	−16.27
Aeliteflo LV	40.25	−35.86	16.31	−19.14	13.07	−19.27	35.58	−34.87	35.54	−15.60
Glaze	40.85	−34.90	16.42	−18.59	13.18	−18.59	36.00	−34.10	35.68	−15.27
Aeliteflo	40.88	−34.85	16.42	−18.59	13.18	−18.59	36.02	−34.07	35.68	−15.27
Revolution	41.20	−34.34	16.48	−18.29	13.24	−18.22	36.25	−33.64	35.81	−14.96
Starflow	41.41	−34.01	16.52	−18.10	13.27	−18.04	36.39	−33.39	35.88	−14.79
Florestore	41.60	−33.71	16.55	−17.95	13.3	−17.85	36.52	−33.15	35.95	−14.63
Ultraseal XT plus	42.08	−32.94	16.62	−17.60	13.38	−17.36	36.85	−32.55	36.11	−14.25
Versaflow	43.61	−30.50	16.84	−16.51	13.61	−15.94	37.91	−30.61	36.54	−13.23
Snowhite B	43.71	−30.34	16.85	−16.46	13.63	−15.81	37.98	−30.48	36.57	−13.16
Crystalessence	43.75	−30.28	16.85	−16.46	13.63	−15.81	38.01	−30.42	36.58	−13.13
Tetric flow	44.07	−29.77	16.89	−16.26	13.68	−15.50	38.23	−30.02	36.65	−12.97
Permaflow	44.56	−28.99	16.94	−16.01	13.75	−15.07	38.57	−29.40	36.76	−12.70

found at a maximum of 38.57 MPa in the control model. Creating an elastic layer with flowable composites was found to decrease the maximum stress in all test models by 29.40 to 35.46%.

Maximum stress in the composite resin was also found at the cavosurface margin. The polymerization shrinkage of the resin composite created stress not only in the bonded substrates but also in the material itself.

Creating an elastic layer with a flowable composite decreased the maximum stress in all test models. It was found that the material's internal stress was reduced by 12.70 to 16.27%.

The total elastic strain energy density (ESEDEN) was highest in the control model (0.1742 MPa/1,000). This value represented the amount of strain energy density in each component of the model. It was found that the strain energy was most concentrated in the adhesive layer near the cavosurface margin in all models. However, maximum strain energy in the model with an elastic layer, which ranged from 0.0752 to 0.0901 MPa/1,000, was less than that of the control model (with maximum ESEDEN of 0.1742 MPa/1,000) at the adhesive layer. A sample of ESEDEN in the cavity model with Aeliteflo as the lining material is shown in Figs. 3A and B. Lining the cavity with flowable composite decreased the strain found in all test models as shown in Table 3.

Effect of the occlusal force

An occlusal force (50 N) was applied at the central groove and created stress in the composite in all models. Maximum stress was found in the control model (Fig. 4A). Flowable composite lining was found to decrease maximum stress in all test models. A sample of a stress pattern in the cavity model with Aeliteflo as the lining material is demonstrated in Fig. 4B.

The occlusal force increased stress in all parts of the tooth-restoration system. In the enamel, maximum stress was found at the cavosurface margin, and the greatest maximum stress (81.21 MPa) was found in the control model. The creation of an elastic layer with flowable composites reduced the maximum stress at each substrate. The maximum stress created by the occlusal force is shown in Table 4.

For dentine, the maximum stress (21.14 MPa) was found at the dentine-enamel junction (DEJ) in the control model. The stresses at the DEJ were reduced by application of flowable composite liners.

The hybrid layer, a thin layer in the resin-dentin interdiffusion zone, was affected by the occlusal force near the DEJ. The flowable composite lining reduced the maximum stress in this structure from 1.92 to 2.27%.

The maximum stresses in the adhesive layer were found at the cavosurface of restoration in all models. Greatest maximum stress in the adhesive layer (70.13 MPa) was found in the control model. The flowable composite lining was found to reduce maximum stress in this layer. The amount of stress reduction ranged from 23.14 to 28.16%.

Resin composite was the most affected structure by occlusal force because the force was directly applied to this structure. Greatest maximum stress was found in the control model. The flowable composite lining was determined to slightly reduce stress in this structure. The amount of stress reduction ranged from 0.17 to 0.34%.

The ESEDEN of the control model and that of a representative cavity model with lining material (Aeliteflo) is demonstrated in Figs. 3C and D. The strain was found at the applied location on the composite. Lining the cavity with flowable composite was able to increase the strain found in all test models from 0.61 to 1.21%, as demonstrated in Table 3.

Linear relationship analysis

A correlation and linear regressive model was analyzed. The results are presented by substrate (enamel, dentine, hybrid layer, adhesive layer and resin composite) in Table 5.

For enamel, all flowable composites were found to reduce the stress from polymerization shrinkage. Linear regression analysis revealed the linear equation $y=1247.68x–43560.23$, $r^2=0.987$. When the greatest maximum stress in the control model was considered in this equation, it was found that stress reduction in enamel could be expected when using a flowable composite with an elastic modulus below 34,731.69 MPa. Thus, the flowable composite lining was also found to reduce stress from occlusal force in enamel. Linear regression analysis revealed that the stress reduction could be expected when using flowable composites with elastic modulus below 32,645.27 MPa.

For dentine, all flowable composites were found to reduce polymerization shrinkage stress. Linear regression analysis revealed the linear equation $y=8194.14x–127080.77$, $r^2=0.963$. With this equation, the proper elastic modulus of flowable composites to reduce maximum stress in dentin was calculated. It was found that stress from polymerization shrinkage could be reduced in dentin when using a flowable composite lining with elastic modulus below 387,101.52 MPa. All flowable composite linings were found to reduce stress caused by the occlusal force. It was estimated through the linear regression analysis that stress reduction could be expected when using flowable composites with an elastic modulus below 672,238.74 MPa.

For the hybrid layer, all flowable composite linings were able to reduce stress from polymerization shrinkage in the hybrid layer. Linear regression analysis provided the linear equation $y=7813.11x–95504.09$, $r^2=0.977$. It was estimated that stress reduction in the hybrid layer could be expected when using flowable composites with an elastic modulus below 394,768.56 MPa. Occlusal force stress reduction in the hybrid layer was observed in all test models. The results could not be analyzed with linear regression methods.

For the adhesive layer, polymerization shrinkage stress reduction was observed in all models with a flowable composite lining. A linear equation was obtained. Calculation revealed that stress reduction could be expected when using flowable composites with elastic modulus below 44,560.02 MPa. Thus, all flowable composites were found to reduce occlusal force in the adhesive layer. Linear regression analysis revealed that stress reduction could be expected when using flowable composites with an elastic modulus below 57,279.33 MPa.

For the resin composite, lining with flowable

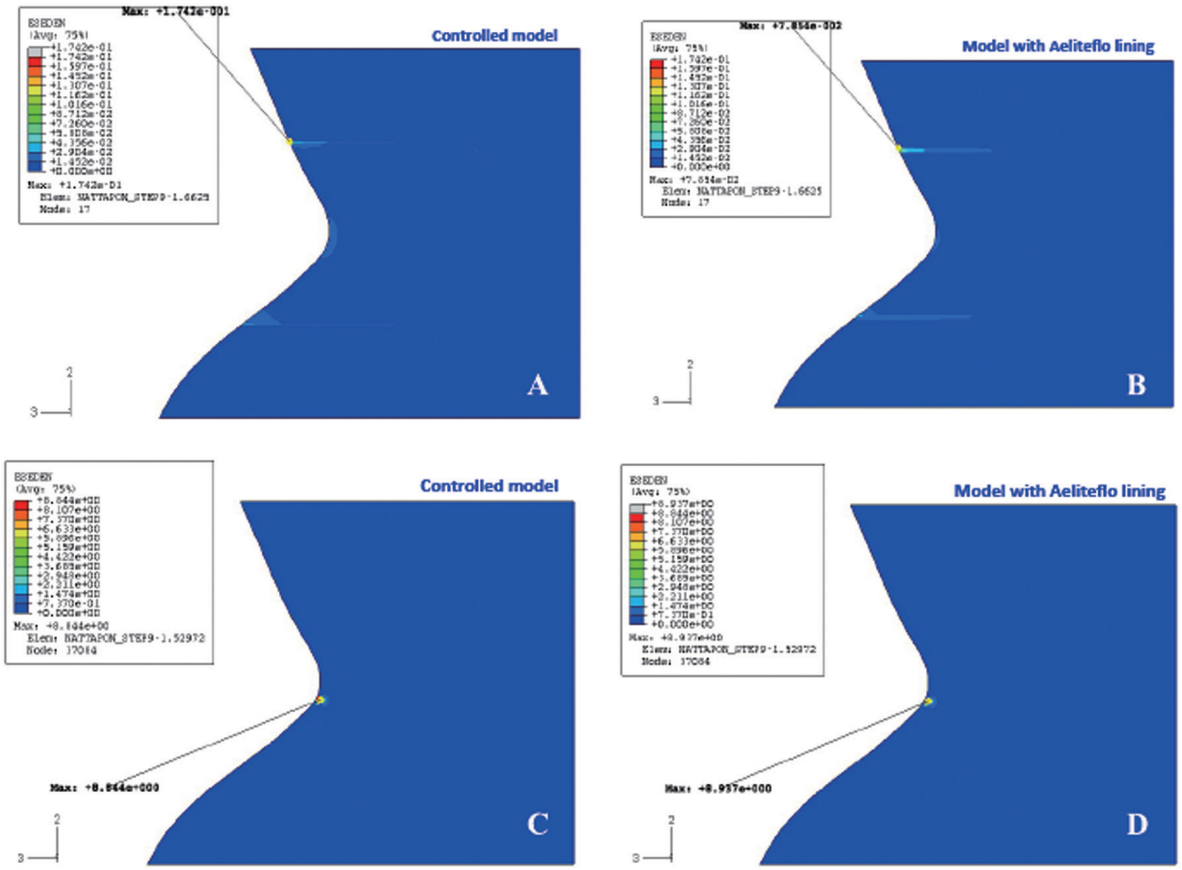


Fig. 3 ESEDEN pattern as affected by the polymerization shrinkage (A and B) and occlusal force (C and D) in the control model (A and C) and the model lined with flowable composite (B and D).

Table 3 Maximum ESEDEN and percentage of strain reduction with the effect of polymerization shrinkage and occlusal loading

Materials	Polymerization shrinkage models		Occlusal loading models	
	Strain	Percentage different	Strain	Percentage different
Control	0.1742	0.00	8.844	0.00
Durafill flow	0.0752	−56.83	8.951	+1.21
Aeliteflo LV	0.0766	−56.03	8.945	+1.14
Glaze	0.0784	−54.99	8.938	+1.06
Aeliteflo	0.0785	−54.94	8.937	+1.05
Revolution	0.0795	−54.36	8.934	+1.02
Starflow	0.0801	−54.02	8.931	+0.98
Florestore	0.0807	−53.67	8.929	+0.96
Ultraseal XT plus	0.0822	−52.81	8.924	+0.90
Versaflow	0.0871	−50.00	8.907	+0.71
Snowhite B	0.0874	−49.83	8.906	+0.70
Crystalessence	0.0875	−49.77	8.906	+0.70
Tetric flow	0.0885	−49.20	8.903	+0.67
Permaflow	0.0901	−48.28	8.898	+0.61

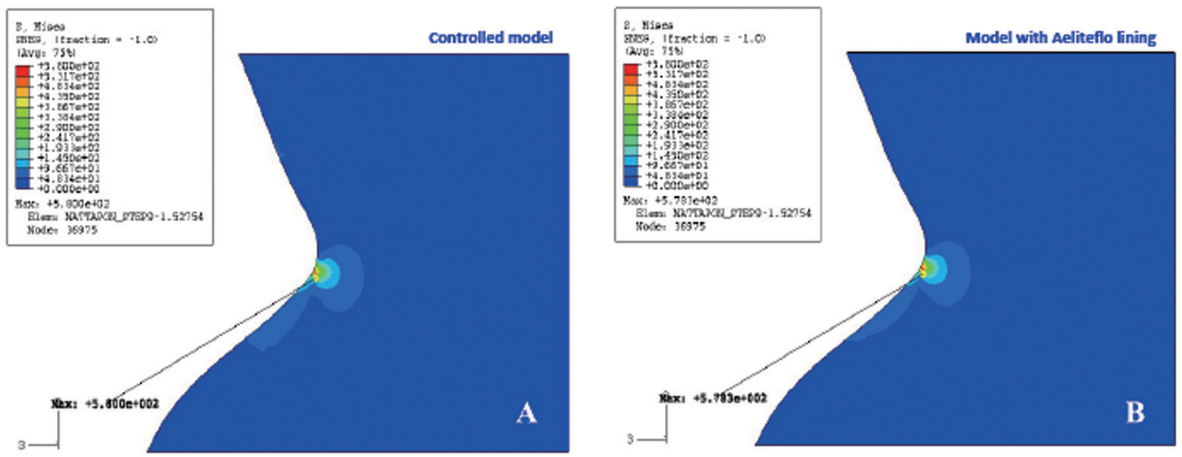


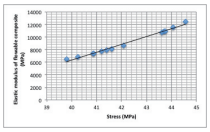
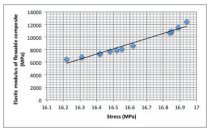
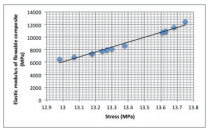
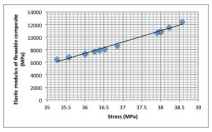
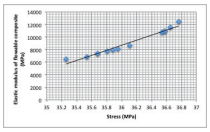
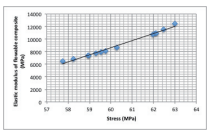
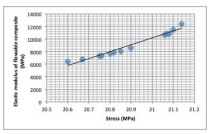
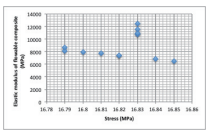
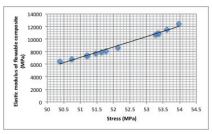
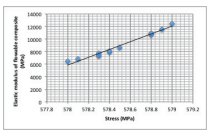
Fig. 4 Von Mises stress pattern as affected by occlusal force in the control model (A) and the test model (B).

Table 4 Maximum Von Mises stresses (MPa) by the effect of occlusal loading and percentage differences from control groups in each substrate

Materials	Enamel		Dentine		Hybrid layer		Adhesive layer		Composite	
	Stress	Percentage different	Stress	Percentage different	Stress	Percentage different	Stress	Percentage different	Stress	Percentage different
Control	81.21	0.00	21.73	0.00	17.18	0.00	70.13	0.00	580.0	0.00
Durafill flow	57.74	−28.90	20.60	−5.20	16.85	−1.92	50.38	−28.16	578.0	−0.34
Aeliteflo LV	58.25	−28.25	20.67	−4.88	16.84	−1.98	50.74	−27.65	578.1	−0.33
Glaze	58.92	−27.45	20.75	−4.51	16.82	−2.10	51.2	−26.99	578.3	−0.29
Aeliteflo	58.95	−27.41	20.76	−4.46	16.82	−2.10	51.22	−26.96	578.3	−0.29
Revolution	59.31	−26.97	20.80	−4.28	16.81	−2.15	51.47	−26.61	578.3	−0.29
Starflow	59.54	−26.68	20.82	−4.19	16.80	−2.21	51.63	−26.38	578.4	−0.28
Florestore	59.75	−26.42	20.85	−4.05	16.79	−2.27	51.77	−26.18	578.4	−0.28
Ultraseal XT plus	60.28	−25.77	20.90	−3.82	16.79	−2.27	52.13	−25.67	578.5	−0.26
Versaflow	61.96	−23.70	21.06	−3.08	16.83	−2.04	53.27	−24.04	578.8	−0.21
Snowhite B	62.06	−23.58	21.07	−3.04	16.83	−2.04	53.34	−23.94	578.8	−0.21
Crystalessence	62.11	−23.52	21.08	−2.99	16.83	−2.04	53.37	−23.90	578.8	−0.21
Tetric flow	62.47	−23.07	21.10	−2.90	16.83	−2.04	53.61	−23.56	578.9	−0.19
Permaflow	63.00	−22.42	21.14	−2.72	16.83	−2.04	53.97	−23.04	579.0	−0.17

composites was also found to reduce polymerization shrinkage stress. It was estimated from the linear equation that stress reduction in this structure could be expected when using flowable composites below 116,243.35 MPa. In addition, a flowable composite lining was found to reduce the stress from occlusal force in resin composites. Linear regression analysis revealed that stress reduction could be expected when using flowable

Table 5 Linear relationship analysis of maximum stress and elastic modulus of flowable composite

Substrates	Enamel	Dentine	Hybrid layer	Adhesive layer	Composite
Effect of polymerization shrinkage					
	y=1247.68x −43560.23 r^2=0.987	y=8194.14x −127080.77 r^2=0.963	y=7813.11x −95504.09 r^2=0.977	y=1800.02x −57391.24 r^2=0.986	y=4020.35x −136033.61 r^2=0.964
Effect of occlusal force					
	y=1132.11x −59293.38 r^2=0.986	y=10995.57x −220711.50 r^2=0.963	r^2=0.025	y=1661.63x −77661.64 r^2=0.985	y=6207.76x −358200.00 r^2=0.973

y: elastic modulus of flowable composite; x: maximum stress occurred on substrate, r^2: goodness-of-fit of linear regression

composites with elastic modulus below 145,932.19 MPa.

All equations demonstrated that reducing the stress within any substrates to zero required a flowable composite with an elastic modulus of negative value.

DISCUSSIONS

The FEA has several advantages over photoelastic analysis when performing stress studies. Although these 2 methods are able to show stress result patterns in a tooth-restoration system, FEA can also provide a numerical result within each structure without any additional measuring technique[22]. Each model created in this study represented a magnified class I restoration. Class I was chosen because it is the cavity with the highest C-factor on the occlusal surface[8]. All models are simulations of a tooth-restoration system consisted of enamel, dentin, a hybrid layer, an adhesive layer, and resin composite. The test models also received a flowable composite liner. Polymerization shrinkage was simulated by means of temperature shrinkage[23]. This method simulated volumetric shrinkage of resin composite towards the center of the material, which was similar to the polymerization of chemical-cured resin composites. For light-cured resin composites, the center of volumetric shrinkage was theorized to be adjacent to the location of the applied curing light. Therefore, different stress result patterns could be expected.

All components in the models were assumed to be isotropic, linearly elastic and perfectly bounded together. Hence, the results for maximum Von Mises stress could not be interpreted by way of interfacial stress but only by stress gathered in these components. As a result, adhesive failure or de-bonding of each component was neglected in this study. The polymerization shrinkage stress stored in each component was a crucial factor because it determined the pre-loaded condition and the integrity of the tooth-restoration system[22]. Additionally, the results of this study provide information regarding the effect of the polymerization shrinkage stress generated in both individual and combined components.

In this study, the control model received a resin composite restoration without any methods of stress relief (liner). The results revealed that stress was highest at the enamel margin. Enamel is the structure whose elastic modulus is highest within the tooth-restoration system. Therefore, enamel did not yield to the applied force and resulted in increased stress. This finding was in agreement with the study of Haak and co-workers, who stated that marginal enamel fractures were frequently found after polymerization shrinkage[24]. Flowable composite lining was the method of stress relief chosen for this study. A flowable composite liner in this study represented a pre-cured layer surrounding the bulk of the resin composite. This layer gave additional thickness to the pre-existing adhesive layer and enhanced compliance to the system[25]. It was concluded that all flowable composite liners were able to decrease stress in the enamel.

Flowable composite liners have unique flowability due to a 20–25% reduction of the filler content compared to the conventional hybrid composite. This characteristic results in inferior mechanical properties and, therefore, limited usage[14,26]. Flowable composites have not been recommended for restorations in high stress-bearing areas. Nevertheless, the composites' low mechanical properties have been demonstrated to be useful for lining the base of resin composite restorations and counteracting the effects of polymerization shrinkage by conventional hybrid composites (described as the elastic cavity wall concept)[10,11,13]. Several types of flowable composites with different compositions are available

today, leading to differences in mechanical properties, especially in terms of elastic modulus. The present study investigated the application of thirteen different flowable composites (Table 1) used as liners in 2-dimensional class I cavity models. The elastic modulus of these flowable composites ranges from 6,499 to 12,484 MPa[27]. This wide difference is due to the filler volume fraction in each material[28-31]. Filler particles were added to improve the resin composite's mechanical properties and handling characteristics. A decreased filler volume fraction resulted in reduced flexural strength, hardness, fracture toughness and viscosity[30-32]. In this study, creating an elastic cavity wall with flowable composite liners could be achieved regardless of the type of flowable composite used. Nevertheless, stress reduction was mostly observed when Durafill Flow was used as an elastic layer (liner). According to Labella and co-workers, the elastic modulus of Durafill Flow was the lowest amongst flowable composites used in their study[27]. Durafill Flow was composed of 40% filler in volume, which was also found to be the smallest filler volume fraction amongst all tested flowable composites[30].

The hybrid layer was found to have a lower elastic modulus than that of the normal dentin and be beneficial in terms of stress relieve[12]. Our results show that some polymerization shrinkage stress was increased within this thin layer, being initially concentrated on the angle of the cavity and then transferred to the surrounding dentin. Shrinkage stress reduction could not be relied on the hybrid layer alone because this structure was very thin. In the present study, lining with flowable composites was able to reduce shrinkage stress in the hybrid layer, regardless of the elastic modulus of the material. This could be explained by the increase in thickness of the elastic layer due to the flowable composite liner.

Stress from the occlusal force was concentrated in the structure that had direct contact with the resin composite. From there, the stress was transferred to the surrounding structure, and substrates at the cavosurface were found to be the most affected. By creating a more compliant cavity wall, stress in these structures was lessened. This revealed that the elastic wall could counteract the stress from both the polymerization shrinkage and occlusal force. This result supported a previous study that found the increasing flexibility of the cavity wall could reduce microleakage due to an occlusal force[32]. This finding could be applied to a clinical situation where flowable composite liners with the proper elastic modulus could be used to sustain the integrity of the enamel and the adhesive layer, keeping these structures intact longer than in a situation without a liner. The linear relationship analysis showed that a flowable composite liner with a lower elastic modulus led to a more effective stress reduction in any of the substrates. Because the flowable composites presented in this study had an elastic modulus lower than expected values, all of them of them could reduce the stress, to different extents, from a shrinkage force of Z250 and an occlusal force of 50 N. However, based on the linear equation, there were no flowable materials that could compensate for all the stress in the tooth-restoration system, which would have required a flowable material with a negative elastic modulus. As there is no such material, stress is expected to remain in the system and potentially affect the clinical outcome of composite restorations. Additional techniques such as the soft-start or pulse-delay curing method[33,34] and the use of low shrinkage composites[35,36] might be recommended to compensate for the remaining stress.

CONCLUSIONS

The substrates (enamel and adhesive layer) at the cavosurface were ones the most affected by shrinkage stress. Thus, the strain energy due to shrinkage stress was most concentrated in the adhesive layer at the cavosurface margin. This property might have made the material more vulnerable to fatigue failure. The stress and strain energy should be reduced by lining the class I cavity with flowable composite. The linear equation acquired from the analysis of results revealed that the proper elastic modulus of flowable composites to be used for the elastic wall should be less than 34,672.5 MPa. Flowable composites with this elastic property should reduce polymerization shrinkage stress in all structures of tooth restoration systems.

The occlusal force had a great impact on the contracted area of the substrate. The stress transferred prominently to the substrates (enamel and adhesive layer) at the cavosurface. The use of a flowable composite as liner clearly reduced the maximum stress at the cavosurface. Analysis of the results obtained after application of the occlusal force revealed that the proper elastic modulus of flowable composites used for the elastic wall should be less than 14,500 MPa to buffer the stress created by the occlusal force.

REFERENCES

1) Christensen GJ. Longevity of posterior tooth dental restoration. J Am Dent Assoc 2005; 136: 201-203.
2) Kleverlaan CJ, Feilzer AJ. Polymerization shrinkage and contraction stress of dental resin composites. Dent Mater 2005; 21: 1150-1157.
3) Davidson CL, de Gee AJ, Feilzer AJ. The competition between the composite-dentine bond strength and the polymerization contraction stress. J Dent Res 1984; 63: 1396-1399.
4) Davidson CL, Feilzer AJ. Polymerization shrinkage and polymerization shrinkage stress in polymer-based restoratives. J Dent 1997; 25: 435-440.
5) Carvalho RM, Pereira JC, Yoshiyama M, Pashley DH. A review of polymerization contraction: the influence of stress development versus stress relief. Oper Dent 1996; 21: 17-24.
6) Duncanson MG Jr, Korostoff E. Compressive visco elastic properties of human dentine: I. Stress-relaxation behavior. J Dent Res 1975; 54: 1207-1212.
7) Braga RR, Ballester RY, Ferracane JL. Factors involved in the development of polymerization shrinkage stress in resin-composites: A systematic review. Dent Mater 2005; 21: 962-970.
8) Feilzer AJ, de Gee AJ, Davidson CL. Setting stress in composite resin in relation to configuration of the restoration. J Dent Res 1987; 66: 1636-1639.

9) Braga RR, Ferracane JL. Contraction stress related to degree of conversion and reaction kinetics. J Dent Res 1987; 81: 114-118.
10) Unterbrink GL, Liebenberg HL. Flowable resin composites as "filled adhesives": literature review and clinical recommendations. Quintessence Int 1999; 30: 249-257.
11) Frankenberger R, Lopes M, Perdigão J, Ambrose WW, Rosa BT. The use of flowable composites as filled adhesives. Dent Mater 2002; 18: 227-238.
12) Van Meerbeek B, Willems G, Celis JP, Roos JR, Braem M, Lambrechts P, Vanherle G. Assessment by nano-indentation of the hardness and elastic of the resin-dentine bonding area. J Dent Res 1993; 72: 1434-1442.
13) Kemp-Scholte CM, Davidson CL. Complete marginal seal of class V resin composite restorations effected by increased flexibility. J Dent Res 1990; 69: 1240-1243.
14) Bayne SC, Thompson JY, Swift EJ Jr, Stamatiades P, Wilkerson M. A characterization of first-generation flowable composites. J Am Dent Assoc 1996; 129: 567-577.
15) Condon JR, Ferracane JL. Assessing the effect of composite formulation on polymerization stress. J Am Dent Assoc 2000; 131: 497-503.
16) De Munck J, Mine A, Vivan Cardoso M, Van Landuyt KL, Lührs AK, Poitevin A, Hanabusa M, Kuboki T, Van Meerbeek B. Hydrolytic stability of three-step etch-and-rinse adhesives in occlusal class-I cavities. Clin Oral Investig 2013; 17: 1911-1918.
17) Pashley DH, Tay FR, Breschi L, Tjäderhane L, Carvalho RM, Carrilho M, Tezvergil-Mutluay A. State of the art etch-and-rinse adhesives. Dent Mater 2011; 27: 1-16.
18) Palin WM, Fleming GJP, Nathwani H, Burke FJ, Randall RC. In vitro cuspal deflection and microleakage of maxillary premolars restored with novel low-shrink dental composites. Dent Mater 2005; 21: 324-335.
19) Meira JB, Braga RR, Carvalho AC, Rodrigues FP, Xavier TA, Ballester RY. Influence of local factors on composite shrinkage stress development- a finite element analysis. J Adhes Dent 2007; 9: 499-503.
20) Rosentritt M, Behr M, Van der Zel JM, Feilzer AJ. Approach for valuating the influence of laboratory simulation. Dent Mater 2009; 25: 348-352.
21) Perillo L, Sorrentino R, Apicella D, Quarata A, Gherlone A, Gherlone E, Ferrari FZ, Aversa R, Apicella A. Nonlinear visco-elastic finite element analysis of poecelain veneers: A submodelling approach to strain and stress distributions in adhesive and resin cement. J Adhes Dent 2010; 12: 403-413.
22) Versluis A, Tatbirojn D, Pintado MR, DeLong R, Douglas WH. Residual shrinkage stress distributions in molars after composite restoration. Dent Mater 2004; 20: 554-564.
23) Pongprueksa P, Kuphasuk W, Senawongse P. The elastic moduli across various types of resin/dentine interfaces. Dent Mater 2008; 24: 1102-1106.
24) Haak R, Wicht MJ, Noack MJ. Marginal and internal adaptation of extended class I restorations lined with flowable composites. J Dent 2003; 31: 231-239.
25) Kemp-scholte CM, Davidson CL. Marginal integrity related to bond strength and strain capacity of composite resin restorative systems. J Prosthet Dent 1990; 64: 658-664.
26) Attar N, Tam LE, McComb D. Flow strength, stiffness and radiopacity of flowable resin composites. J Can Dent Assoc 2003; 69: 516-521.
27) Labella R, Lambrechts P, Van Meerbeek B, Vanherle G. Polymerization shrinkage and elasticity of flowable composites and filled adhesives. Dent Mater 1999; 15: 128-137.
28) Bonilla ED, Yashar M, Caputo AA. Fracture toughness of nine flowable resin composites. J Prosthet Dent 2003; 89: 261-267.
29) Baroudi K, Saleh AM, Silikas N, Watts DC. Shrinkage behavior of flowable resin-composites related to conversion and filler-fraction. J Dent 2007; 35: 651-655.
30) Kim KH, Ong JL, Okuno O. The effect of filler loading and morphology on the mechanical properties of contemporary composites. J Prosthet Dent 2002; 87: 642-649.
31) Braem M, Finger W, Van Doren VE, Lambrechts P, Vanherle G. Mechanical properties and filler fraction of dental composites. Dent Mater 1989; 5: 346-348.
32) Senawongse P, Pongprueksa P, Tagami J. The effect of the elastic modulus of low-viscosity resins on the microleakage of class V resin composite restorations under occlusal loading. Dent Mater J 2010; 29: 324-329.
33) Piccioni MA, Baratto-Filho F, Kuga MC, Morais EC, Campos EA. Cuspal movement related to different polymerization protocols. J Contemp Dent Pract 2014; 15: 26-28.
34) Tauböck TT, Feilzer AJ, Buchalla W, Kleverlaan CJ, Krejci I, Attin T. Effect of modulated photo-activation on polymerization shrinkage behavior of dental restorative resin composites. Eur J Oral Sci 2014; 122: 293-302.
35) Kim RJ, Kim YJ, Choi NS, Lee IB. Polymerization shrinkage, modulus, and shrinkage stress related to tooth-restoration interfacial debonding in bulk-fill composites. J Dent 2015; 43: 430-439.
36) Marovic D, Tauböck TT, Attin T, Panduric V, Tarle Z. Monomer conversion and shrinkage force kinetics of low-viscosity bulk-fill resin composites. Acta Odontol Scand 2015; 73: 474-480.